NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

ANALYSIS AND COST OPTIMIZATION OF A USCG REMOTE HYBRID POWER SYSTEM

by

Zachary A. Weiss

June 2002

Thesis Advisor:	John G. Ciezki
Second Reader:	Sherif Michael

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REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY	**2. REPORT DATE** June 2002	**3. REPORT TYPE AND DATES COVERED** Master's Thesis

4. TITLE AND SUBTITLE: Analysis and Cost Optimization of a USCG Remote Hybrid Power System	**5. FUNDING NUMBERS**
6. AUTHOR(S) Zachary A. Weiss	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.	**12b. DISTRIBUTION CODE**

13. ABSTRACT

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14. SUBJECT TERMS Hybrid Power System, Lead Acid Batteries, USCG Alaskan National Distress System, Solar Energy, Cost Optimization	**15. NUMBER OF PAGES** 125
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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ANALYSIS AND COST OPTIMIZATION OF A USCG REMOTE HYBRID POWER SYSTEM

Zachary A. Weiss
Lieutenant Junior Grade, United States Coast Guard
B.S., United States Coast Guard Academy, 1998

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
June 2002

Author: Zachary A. Weiss

Approved by: John Ciezki
Thesis Advisor

Sherif Michael
Second Reader

Jeffrey Knorr
Chairman, Department of Electrical and Computer Engineering

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ACKNOWLEDGMENTS

I wish to recognize my thesis advisor, Dr. John Ciezki, for his guidance, attentiveness, flexibility, and support. Thank you for contributing to this thesis, my graduate education, and my overall experiences since our professional relationship commenced.

Thanks to Dr. Sherif Michael for his comments and suggestions as second reader.

Many thanks to Garth Corey, Sandia National Laboratories, for the numerous hours spent teaching me battery theory and providing me with lead-acid battery information. I look forward to working with you in the future.

Thanks to Chris Doreleyers, Mechron Power Systems, for providing me with information and explanations regarding the control system employed by the hybrid power system.

Thanks to Charles Pomaski, U.S. Coast Guard, for sending (multiple times) me data that was crucial to the completion of this study.

Special thanks to Dan Slagle, U.S. Coast Guard, for listening to the many ideas (some quite preposterous) I had regarding this thesis. Your experience with and knowledge of the communications sites allowed for the timely completion of my study.

Finally, I would like to thank all who have listened and offered advice. The support you provided me helped alleviate some of the stress inherent in the thesis process.

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EXECUTIVE SUMMARY

An analysis has been conducted to minimize the cost of operating two Alaskan National Distress System (NDS) sites, namely Robert Barron Peak (Robert Barron) and Duke Island. United States Coast Guard (USCG), Maintenance and Logistics Command Pacific (MLCPAC), Command, Control, and Communications (TE-3) maintains the NDS VHF-FM communications sites to assist mariners in distress. The sites operate off the commercial power-grid, requiring remote hybrid power to be supplied by propane generators, photovoltaic arrays, and Valve Regulated Lead Acid (VRLA) batteries.

The two costs discussed in this thesis include propane to fuel the generators and batteries to store energy. The development and creation of a spreadsheet to minimize cost by optimizing two generator controller settings are the crux of the analysis. One generator setting is used to control the depth of discharge (DOD) while the other setting controls the percent recharge for each battery in the eight-battery bank at each site. The DOD of a battery is determined by dividing the number of Amp-Hours discharged away from the battery's rated capacity by the same rated capacity. The percent recharge is the state of charge (SOC) the battery attains at the end of the recharge process. SOC is usually represented as a percent and when multiplied by a battery's rated capacity yields the number of Amp-Hours available to discharge to 100% DOD.

The load current at each site was accounted for by quantifying the contribution made to the load by each piece of electrical equipment. The prices of propane and batteries, including delivery costs, were identified for each site.

Data indicate that USCG MLCPAC TE-3 currently sets the generator controls to allow the batteries to discharge up to 60% DOD prior to initiating the charging process. The charging process concludes once the batteries have been recharged to approximately 85% SOC.

There are several factors that control the time it takes to discharge and recharge a battery. These factors include discharge rate, battery temperature, DOD, and percent recharge. In general, as the discharge rate of a battery, which is dependent on the load current, decreases, the rated capacity increases. As temperature decreases below 77°F, the rated capacity decreases resulting in a new available capacity that can be discharged. The length of time it takes to discharge a battery is found by taking the available capacity at a specific discharge rate and temperature, and then, experimentally measuring the battery's SOC until 100% DOD is reached during the discharge process. Manufacturers provide performance curves for various discharge rates to help users determine the number of hours available at different DODs. Using one of these curves, the maximum time to 100% DOD is found by multiplying the corresponding number of hours at 100% DOD by the proper temperature correction factor for a particular discharge rate. The maximum time is then multiplied by the percent determined from subtracting the SOC at a particular DOD from the SOC at a specific percent recharge. The result is the actual discharge time a user can expect during normal battery usage without solar power. The time it takes to recharge a battery is nonlinearly reduced as DOD or percent recharge decreases.

Since the NDS sites all contain photovoltaic arrays, it is necessary to account for the time when the load is supported only by solar power. Each time a battery is discharged and recharged, a cycle occurs. Therefore, to determine the number of hours added to a discharge cycle, the total time during the year that the photovoltaic arrays maintain the load is divided by the number of battery cycles. The discharge time without solar power and the solar time added per cycle result in the actual discharge time. Once the recharge time and discharge time are known, the number of times the generator cycles in a year is easily computed.

Battery life is given in terms of available cycles. As the DOD increases, the number of battery cycles available nonlinearly decreases. As mentioned before, a battery cycle occurs when it is discharged and consequently recharged. Therefore, one battery cycle is counted, at a particular DOD, each time the generator starts for the purpose of charging the batteries. Additionally, every time the photovoltaic arrays provide power, one battery cycle is counted at a specific DOD.

The spreadsheet iterates in 5% increments among all physically possible combinations of battery DOD and percent recharge that can be manually set to control the generator start level and duration of the generator run-time during one charging process to find the optimal DOD and percent recharge that minimize cost. The cost varies as the amount of propane consumed changes due to an increase or decrease in generator run-time. The subsequent change in generator run-time dictates that more or less battery cycles will occur at given depths of discharge. The end result is a balance between the average cost per year of both batteries and propane over the time it takes before the batteries are dead and propane tanks on site are refueled respectively.

An alternative configuration exists that can improve the performance of the power system supporting NDS communications requirements. In the alternative configuration, the SOC of the batteries is increased without any additional generator run-time. However, to properly use the alternative configuration, it is necessary to ensure that an appropriate amount of battery capacity is installed at each site. The reason for this extra capacity is due to allowing one string in a two-string battery bank to charge the other string of batteries while simultaneously supporting the load. The added demand placed on the string engaged in charging and supplying the load is two-pronged. The first reason is due to the load seen by each battery in the string doubling. The second reason for the added demand comes from the increase in load from charging the other string. Ignoring the initial costs of installing new batteries to handle the increased power requirement during the time when one string charges the other string, the alternative configuration provides a cost savings by increasing the discharge time between generator starts.

The results found during the spreadsheet simulations indicate that it is likely that more optimal DOD and percent recharge settings exist than those currently being used. Current generator settings at each site are 60% DOD and 85% recharge. The optimal settings at Duke Island were determined to be 70% DOD and 35% recharge. At Robert Barron, the optimal generator settings were calculated to be 80% DOD and 60% recharge. It is recommended that more experimentation be done with the batteries being used to increase the accuracy of the theoretical discharge and recharge times that are used in the spreadsheet as a result of a lack of manufacturer provided data. Ideally, experiments could be conducted which would provide durations of discharge and recharge time for all possible combinations of discharge rate, DOD, and percent recharge that could feasibly be simulated with the spreadsheet. Furthermore, more simulation testing should be performed and compared to actual data collected at the NDS sites to verify that the spreadsheet functions properly.

I. INTRODUCTION

A. PROBLEM DESCRIPTION

United States Coast Guard (USCG), Maintenance and Logistics Command Pacific (MLCPAC), Command, Control, and Communications (TE-3) operates and maintains the National Distress System (NDS) throughout the coastal waters of Alaska. NDS ensures that mariners in need of assistance can communicate with rescue officials via a VHF-FM network. Due to the nature of the service NDS provides, it is crucial that the system always be online.

NDS consists of several remote VHF-FM communications sites typically located atop mountains in coastal Alaska. The sites are highly susceptible to the unpredictable and harsh wintry weather conditions in the region making it impossible to perform maintenance or fuel the majority of the sites from mid-October through mid-March.

Because of their remote locations and the critical functions they perform, NDS communications sites are expensive to operate and maintain. The primary costs associated with the continued operation of the VHF-FM sites are propane fuel to run the generators and sealed Valve Regulated Lead Acid (VRLA) batteries to store and discharge energy. This thesis documents how to maximize battery life and minimize propane fuel costs at two NDS sites.

Two Alaskan NDS sites, Robert Barron Peak (Robert Barron) and Duke Island, are discussed in this thesis to provide a general representation of the power generation and storage issues of typical VHF-FM communication sites. These sites are at different latitudes and have slightly different power requirements enabling the optimization to be tested over a range of conditions. The methodology applied to these stations may similarly be applied to the remaining NDS sites.

B. PURPOSE OF SYSTEM

The two NDS sites are currently powered by hybrid systems. These systems consist of propane generators, a photovoltaic array, and sealed VRLA batteries connected in parallel to the load. Figure (1-1) shows a block diagram of this hybrid system.

During the months with considerable sunlight, the photovoltaic array generally provides enough power to energize the load and maintain full charge on the batteries. The generator operates primarily in late fall, winter, and early spring to intermittently supply the load and maintain a predetermined state of charge (SOC) for the battery bank.

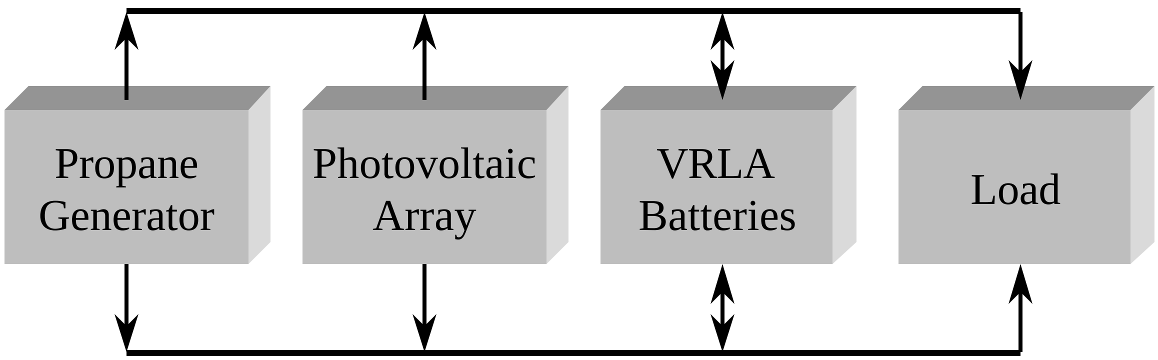

Figure 1-1. Remote Site Hybrid Power System.

C. REQUIREMENT OF REMOTE POWER

1. General

There are many instances when power is not readily accessible from the conventional grid. In these cases it is necessary to produce power through alternative means. This remote power must be cost efficient and reliable. There are several hybrid configurations that meet the needs of their respective power requirements.

2. Standard Configurations

The most common hybrid configurations are formed from various combinations of photovoltaic, wind turbine, fossil fuel, and battery power. For telecommunications applications, there are three major objectives for the power system. Namely, it must provide all of the electrical energy at the site, be available at all times, and efficiently convert from the given energy source into usable electrical energy [1].

Some systems consist of a photovoltaic array and batteries. To ensure the power requirements of the system are met, it is necessary to assess the feasibility of using a system like this prior to its installation. It is necessary to know the power requirements of the load, the amount of sunlight the photovoltaic array will receive, and the frequency of events, such as weather, that may impact the performance of the power system [1]. In a system only powered by a photovoltaic array and batteries, it is crucial that there is enough storage capacity in the batteries to handle the periods when solar power is not available.

Another type of hybrid system used to provide power consists of a wind turbine, photovoltaic array, and batteries. This system functions similar to the one previously discussed with the added flexibility that it can generate power independent of sunlight. The added benefit from the nature of wind extends battery life by preventing SOC from dropping below acceptable levels because it can produce energy during hours of darkness [2]. In order for a wind turbine system to operate in high wind conditions, there is a mechanism that rotates the wind turbine so that it faces away from the wind to avoid mechanical damage. Due to this protection mechanism, there is low output power in high wind conditions [2]. A system with a wind turbine should be used in remote locations where there is enough wind available to supplement the photovoltaic array and battery bank.

Either of the two previously mentioned configurations can be used as the main source of energy for remote applications. However, neither of these systems can guarantee power during prolonged periods without wind and sun. For this reason, it may be necessary to fit a hybrid system with a diesel or propane generator. The main problem with using a diesel or propane generator is with fuel consumption. As a result, it is important to design the system so that the generator runs "…to take full advantage of renewable energy during the periods of time that it is available and to minimize diesel fuel consumption." [3] The main advantage of using a fossil fuel generator is the higher probability that power will be reliably supplied to the application, as compared to a photovoltaic, wind turbine, and battery powered system alone.

3. System Control

Few hybrid power systems can operate without a controller. "The system controller provides supervisory control of all power system elements as well as protection." [4] For example, a controller could be used to start a generator when the voltage of the system drops below a certain threshold. The generator then runs until the system voltage is above a set quantity. The values that are selected need to reflect the operating parameters of each system component. The controller may also perform similar functions to ensure that batteries are not overcharged and wind turbines do not run outside their limits.

D. PAST WORK

In 1993, LCDR Christopher Pietras provided recommendations to USCG MLCPAC TE-3 outlining a possible hybrid power system to be used with NDS. Many of the recommendations have since been implemented. Pietras' work did not specifically detail generator settings that could be used to maximize battery life and minimize propane fuel costs. Due mainly to the high delivery cost of replenishing propane and batteries, and the requirement of high reliability, the NDS site optimization problem is quite different than most hybrid facilities. As a consequence, coupled with the nondeterministic impact of the solar array, an original approach is outlined in this thesis.

E. CHAPTER ORGANIZATION

Chapter II provides a structural, operational, and electrical overview of the equipment located at Robert Barron and Duke Island. Chapter III contains an exposition on basic lead-acid battery theory emphasizing the performance of the Absolyte IIP batteries used at the sites. Additionally, various battery technologies are explored to provide a comparison with basic lead-acid batteries. Chapter IV chronicles the steps necessary to mathematically model both sites including an analysis of data from 2001, extrapolation of battery manufacturer performance curves to estimate values for charging durations at various depths of discharge and percent recharges, and the development of the price per battery and gallon of propane. These steps culminate in the creation of a spreadsheet that simulates the performance of the power system at each site. Chapter V introduces an alternative configuration that could be installed at each site to provide future operational cost savings. Chapter VI documents several simulations predicting operational results and optimal costs associated with each specific simulation. Chapter VII concludes with redesign issues, analysis and research summaries, and recommendations for future work.

II. ROBERT BARRON AND DUKE ISLAND SITE OVERVIEWS

A. POWER AND OPERATIONAL REQUIREMENTS

1. Communication Equipment

Both Robert Barron and Duke Island contain communication equipment used as part of the NDS. The operations taking place at the sites vary, resulting in different power requirements for each site. Table (2-1) summarizes the power required to operate the listed equipment at each site. The load current is calculated by dividing the total power consumed by 24.4 VDC (a convenient value at which measurements were made).

Equipment	Robert Barron	Duke Island
MDS 960A Radio	93.7 W (24.4 VDC)	93.7 W (24.4 VDC)
Multiplexor and Tellabs	11.2 W (24.4 VDC)	11.2 W (24.4 VDC)
PFM	15 W (24.4 VDC)	15 W (24.4 VDC)
#1 Quantar VHF-FM Radio*	66 W (24.4 VDC)	66 W (24.4 VDC)
#2 Quantar VHF-FM Radio*	66 W (24.4 VDC)	66 W (24.4 VDC)
Photovolatic Controller[1]	4.9 W (24.4 VDC)	4.9 W (24.4 VDC)
Weather Transmitter	20 W (12.8 VDC)	20 W (12.8 VDC)
Generator Control Alarm and Monitoring Circuitry	75 W (24.4 VDC)	75 W (24.4 VDC)
State Police Radio*	25 W (12.8 VDC)	Not at Site
FAA Radio*	66.4 W (12.8 VDC)	Not at Site
Forest Services Radio*, 2	20 W (12.8 VDC)	Not at Site
Total Power Consumed	463.2 W	351.8 W
Power Consumed Per Day	11.12 kWh/day	8.44 kWh/day
Load Current (24.4 VDC)	19.0 A	14.4 A

Table 2-1. Site Equipment and Average Power Consumption After [5], [6], [7].

* A duty cycle was used in the calculation of the average power consumed by this device.

1 Only consumes power when the system relies on battery power alone.

2 This radio will be installed in June 2002.

2. Equipment Duty Cycles

a. General

Table (2-1) outlines the average power consumed through the operation of the various equipment. While much of the equipment runs continuously and without a change in the power it consumes, there are particular items that have more complicated operational characteristics.

b. Quantar VHF-FM Radios

There are two identical Quantar radios at each site. When not keyed, each radio consumes 52.2 W. Each radio consumes 327 W when keyed. The amount of time the radios are keyed varies widely depending upon the amount of communication that is necessary to support NDS related operations. During a high operational tempo (OPTEMPO), the radios may have a ten to twenty percent keyed duty cycle. When there is a low OPTEMPO, the keyed duty cycle for the radios is between one and two percent. An overall keyed duty cycle for the radios was determined to be five percent. At a five percent duty cycle, the portion of the power consumption from keying for each radio is 16.4 W (327 W multiplied by 0.05). At a 95 percent duty cycle, the portion of the power consumption when not keying for each radio is 49.6 W (52.2 W multiplied by 0.95). The average power consumed by each Quantar radio is the combination of the load when keyed and not keyed for a total power consumption of 66 W (16.4 W plus 49.6 W) as recorded in Table (2-1). [7]

c. State Police, FAA, and Forest Services Radios

The state police and FAA radios were determined to have keyed duty cycles of ten percent. Due to the different propagation needs of both radios, the average power consumed by the state police radio is lower than the FAA radio. Although the forest services radio is not installed, USCG MLCPAC TE-3 anticipates a keyed duty cycle of ten percent. [7]

3. Online Load Information

Displayed under the PFG (Propane Fuel Generator) Juneau link on the D17 NDS website is load information for several NDS sites including Robert Barron and Duke Island (http://www.ktn.net/~ndsemc). The load current that is provided at this website does not include all of the loads indicated in Table (2-1) [7]. The PFM (Prototype Field

Monitor), Photovoltaic Controller, Generator Control Alarm and Monitoring Circuitry, and Forest Services Radio are not included as part of the load current displayed on the website. Additionally, the website reports the average load over a seven day period, which may vary with the frequency and duration of the time the radios are keyed. As a result, the load current on the website is roughly five to eight Amps less than those illustrated in Table (2-1). [8]

B. PHOTOVOLTAIC POWER

1. System Description

Robert Barron and Duke Island have identical photovoltaic systems. The system consists of four arrays each housing 12 solar panels for a total of 48 panels at the site [5], [6]. The sites use the MSX 60 panel from BP Solar [9]. Figure (2-1) pictures a schematic of the solar panel.

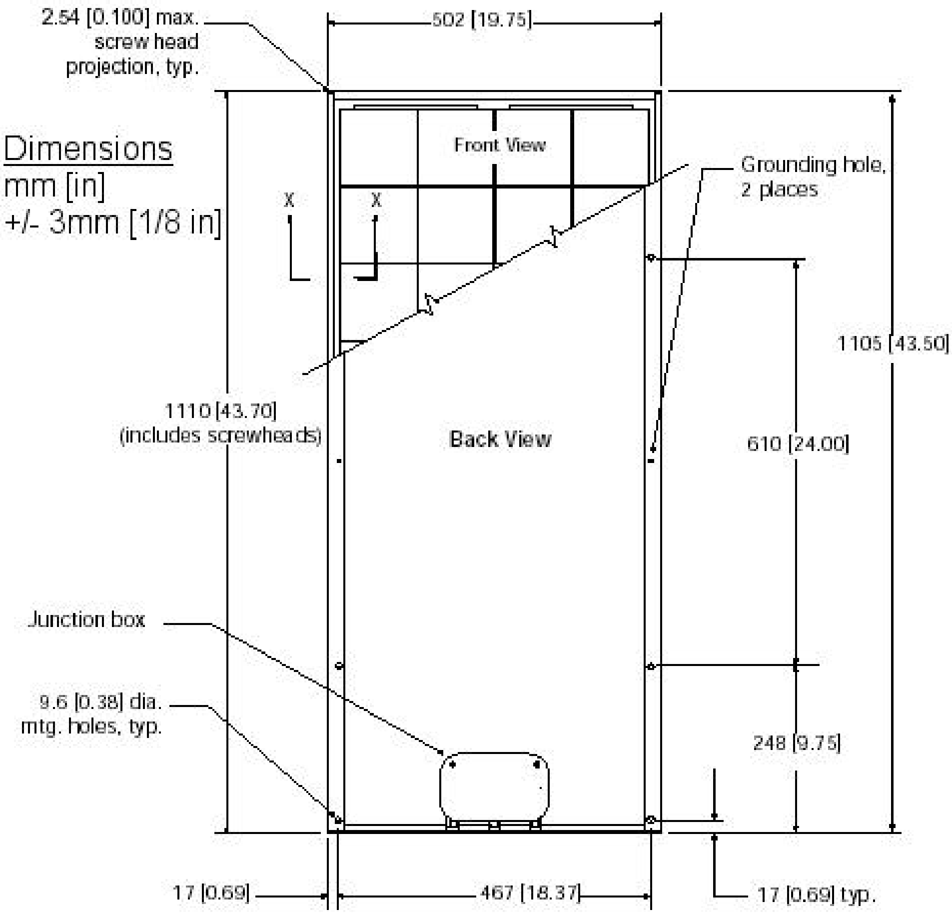

Figure 2-1. BP MSX 60 Schematic From [10].

2. Solar Output Power

The solar panels are connected in such a manner as to produce about 24 VDC. The amount of power that each panel produces depends upon the amount of sunlight that is absorbed. The MSX 60 solar panel is rated at a maximum of 60 W output power [10].

The average insolation contacting a solar panel is computed by multiplying the average daily total insolation by the area of the solar panel, 0.5 m^2. At Robert Barron and Duke Island, the solar arrays are tilted at a fixed angle of 60 degrees. In June (maximum insolation month) at each site, one solar panel receives about 1.92 kWh/day. In December (minimum insolation month), a solar panel at Duke Island receives about 0.66 kWh/day while one at Robert Barron receives about 0.47 kWh/day. Since solar power is planned primarily for the summer, the output power per panel is determined by multiplying the average daily solar insolation per panel in June by 0.10 (ten percent efficiency). At each site in June, a solar panel produces 0.192 kWh/day. Since there are 48 panels at each site, the total power produced by the solar arrays is the product of 48 and 0.192 kWh/day or 9.22 kWh/day ($\frac{9.22kWh}{day} \times \frac{day}{24hr} = 384W$). [11]

3. Parallel Operation

The photovoltaic system is in parallel with the load, batteries, and generators. A photovoltaic controller ensures that the batteries are not overcharged. Additionally, blocking diodes are present to ensure that the solar arrays do not draw power from the batteries when the arrays are receiving little or no sunlight.

The amount of power produced by the photovoltaic arrays varies with the calendar. Solar power provides 90% of the required load from May through September, 10% during April and October, and a negligible amount of power from November through March [12]. When the solar arrays cannot support the entire load, either the batteries or the generators supplement the solar power to seamlessly provide power to operate the communications equipment.

C. BATTERIES

1. System Description

There are eight Absolyte IIP 3-100A17 batteries at Robert Barron and Duke Island. Each battery contains three cells rated at two Volts per cell. Two, four-battery strings of nominal 24 VDC are paralleled to provide power to the load. The batteries in each string are connected in series. The nominal Amp-Hour (AH) capacity of each battery at the 100-hour discharge rate is 1065 AH [13]. Since each string consists only of batteries connected in series, the capacity of each string is 1065 AH. By paralleling the two battery strings, there are a total of 2130 AH stored in the battery banks at each site. The battery banks are in parallel with the photovoltaic arrays, propane generators, and loads. [9]

2. Battery Discharge

As shown in Figure (2-2), there are different discharge profiles for the 100 A Absolyte IIP. Depth of discharge (DOD) is the percent of a battery's original capacity removed during discharge. It is necessary to calculate the current drawn per positive plate of a cell to identify the proper curve to determine the time to a particular DOD.

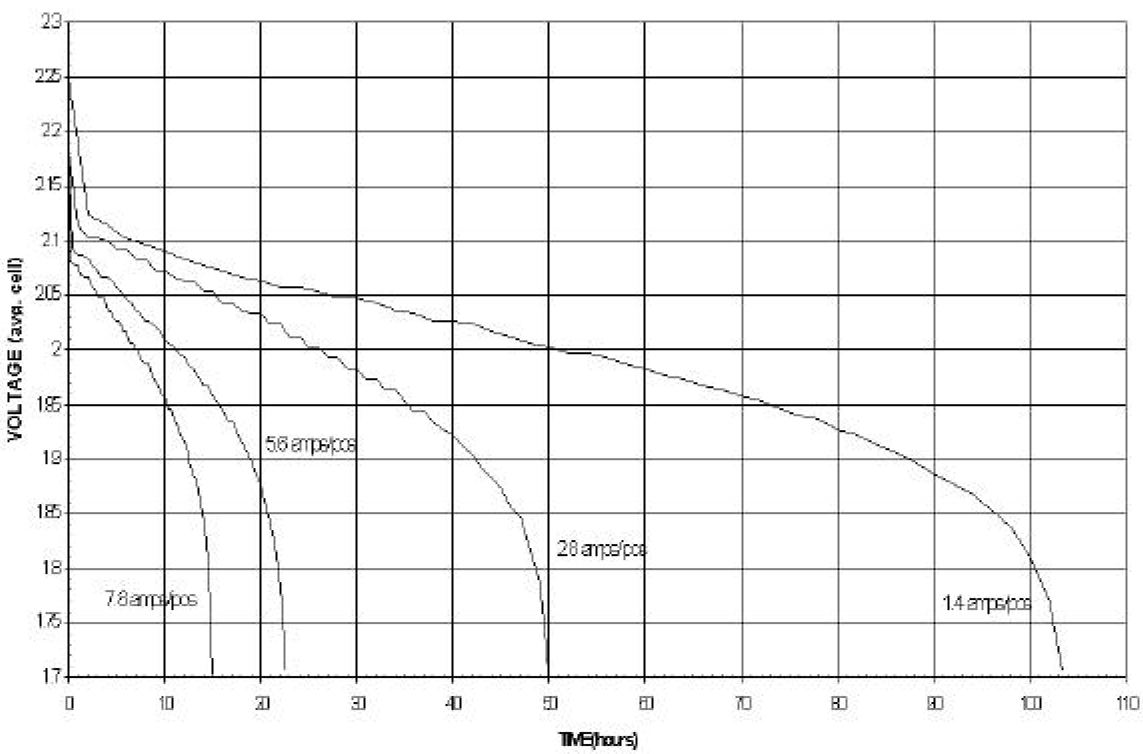

Figure 2-2. Discharge Rates for the Absolyte IIP 100 A Battery From [15].

The batteries at NDS sites are discharged up to 60% DOD (61.2 hours or 102 hours multiplied by 0.6) before the generators are energized. USCG MLCPAC TE-3 selected 60% DOD because it estimates that this DOD is close to the optimal value that minimizes propane fuel consumption and maximizes battery life. Table (2-2) lists operational values obtained for Robert Barron and Duke Island. The current drawn per positive plate is calculated by dividing the battery string current by the number of positive plates (8).

	Robert Barron	**Duke Island**
Cells per Battery	3	3
Positive Plates per Cell	8	8
Current Drawn per Battery String (Load/2)	9.5 A	7.2 A
Current Drawn per Positive Plate	1.19 A	0.90 A
Closest Discharge Curve	1.4 A/pos	1.4 A/pos
Time to 60% DOD	61.2 hours	61.2 hours
Cell Voltage @ 60% DOD	1.98 Volts per Cell (VPC)	1.98 VPC
Battery Potential @ 60% DOD	5.94 V	5.94 V
Battery Bank Potential @ 60% DOD	23.76 V	23.76 V

Table 2-2. Battery Bank Characteristics After [13], [14], [15].

3. Battery Charging

State of charge (SOC) is the percent of a battery's original capacity available for discharge at any given time. When the batteries discharge to 40% SOC, one of the two propane generators automatically energizes and the charging process begins. During this process, the voltage cannot exceed 2.38 VPC according to GNB specifications [13]. Figure (2-3) depicts typical charging profiles for the battery starting at 80% and 100% DOD.

The maximum current capable of being delivered, for charging, by the Mechron control system is 160 A [7]. Since there are two parallel strings, each battery string receives 80 A minus half the current being drawn by the load. In Figure (2-3), the current axis is per 100 AH. To compare the maximum current that can be delivered to each string, the maximum current value on the chart, 18.25 A, must be multiplied by 10.65 (1065 AH divided by 100 AH). The result is 194 A. Therefore, 194 A plus half the load current would need to be provided to each string by the Mechron system to mirror the charging profile shown in Figure (2-3) at 25°C.

When current from the Mechron system (80 A minus half the load) is applied to each battery, the generator recharge voltage (VPC) will quickly increase (less quickly than what is depicted in Figure (2-3)). The generator voltage is allowed to reach 2.38 VPC. At this point, the generator recharge voltage is held constant while the current provided by the Mechron system exponentially decays. As the recharge voltage is maintained, the battery is recharged in a manner similar to that shown by the "% Recharge" curve. The current tail extends as the "% Recharge" curve asymptotically approaches 100%. At the USCG sites, the generators are set to stop charging when the total current (load and charge) is 50 A. This is a compromise between generator run-time (propane fuel consumption) and final percent recharge (related to battery life). For a 19.0 A load, the finish current in Figure (2-3) is 1.46 A $\left(\frac{(50-19)/2}{10.65}\right)$.

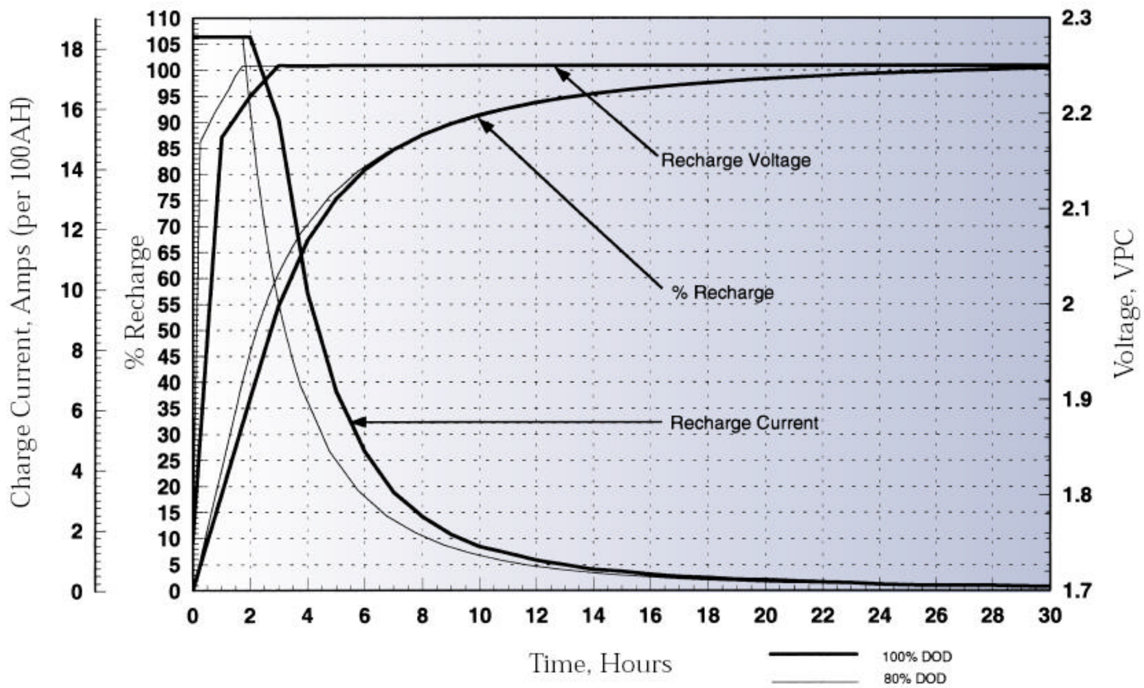

Figure 2-3. Absolyte IIP Recharge Characteristics at 25°C From [16].

Figure (2-3) displays the charging profiles for 100% and 80% DOD (0% and 20% SOC, respectively). Since the batteries in use at Robert Barron and Duke Island are only discharged to 40% SOC, the corresponding three curves would continue to shift left as shown when DOD changes from 100% to 80% DOD.

4. Battery Sizing

The amount of Amp-Hours (AH) required at Robert Barron and Duke Island is the amount of Amp-Hours consumed per day multiplied by the number of days needed for battery backup divided by the maximum DOD. In 1991, using a 240 AH daily load, five days of backup power, and a maximum DOD of 80%, USCG MLCPAC TE-3 calculated that 1500 AH would be necessary at each site. As a result, two strings of four batteries (800 AH at the eight-hour discharge rate) each were installed for a total of 1600 AH at the two sites. For this reason, the Absolyte IIP 3-100A17 battery was used. Once it was determined that the batteries operated at the 100-hour discharge rate, the same battery bank is actually shown to provide 2130 AH. Table (2-3) shows the 1991 backup storage and the anticipated storage during the summer of 2002. [17]

	Robert Barron	**Duke Island**
1991 Daily Load	240 AH/Day	240 AH/Day
Standby Time (8 HR Discharge Rate, 80% DOD)	5.3 Days	5.3 Days
Standby Time (100 HR Discharge Rate, 80% DOD)	7.1 Days	7.1 Days
Standby Time (100 HR Discharge Rate, 60% DOD)	5.3 Days	5.3 Days
2002 Daily Load	456 AH/Day	345.6 AH/Day
Standby Time (100 HR Discharge Rate, 60% DOD)	2.8 Days	3.7 Days

Table 2-3. Battery Standby Time.

The variation between Table (2-2) and Table (2-3) (61.2 hrs versus $2.8 days \times 24 hrs / day = 57.2 hrs$) with regard to discharge duration to 60% DOD is partially due to the non-linear nature of the discharge curve depicted by Figure (2-2). The value obtained in Table (2-2) is the result of multiplying 0.6 and 102 hours (time until 100% DOD). Since the curve in Figure (2-2) exponentially decreases after 90 hours, it is not accurate to assume that 60% DOD takes place at the product of 0.6 and 102 hours. The other source of error arises from using the 1.4 A/pos curve in Figure (2-2), since Robert Barron discharges closer to 1.19 A/pos and Duke Island discharges closer to 0.90 A/pos. Therefore, the standby time in Table (2-3) is a better estimate than the time indicated in Table (2-2). However, the 1.4 A/pos as indicated in Table (2-2) must be used to determine the average cell voltage since it is the closet discharge current value that has a curve associated with it as shown in Figure (2-2).

D. WIND TURBINE POWER

Robert Barron is not fitted with a wind turbine generator. However, Duke Island had a Bergey, BWC 1500, wind power generation system installed in 1999. The generator is rated for 1.5 kW at 24 VDC. There were three potential choices available at the time: 1 kW, 1.5 kW, and a 10 kW generator. The 1.5 kW system was selected because it was significantly cheaper than the 10 kW system and only slightly more expensive than the 1 kW system. It was calculated that during the winter months, the 1.5 kW wind system would provide one-third the power that the photovoltaic arrays produced during the summer months. [17]

The system came equipped with a Bergey controller responsible for maintaining the system during high-wind speeds. When functioning properly during high-wind speeds, the blades would shift to be perpendicular to the wind. This would prevent the blades from being damaged. [17]

The wind energy was converted to electrical power though a three-phase variable frequency generator. The conversion system utilized silicon controlled rectifiers (SCR). The SCRs were triggered in a particular manner to regulate the power below a maximum threshold. [17]

The system was rendered inoperable by the extreme mountainous weather conditions during the first winter it was in place. The system that was used was advertised to withstand wind speeds up to 160 mph. USCG MLCPAC TE-3 estimates that a combination of wind speeds near 160 mph and rapidly changing wind direction was the primary cause of failure. [17]

Despite efforts to employ wind-power generation, there has been no cost-effective solution to combat the lack of reliability of these systems in the extremely volatile weather environment where they are needed for NDS. There are more rugged systems available; however, these wind turbine systems are much more expensive than the ones both currently and previously used. [17]

There are installed systems at other NDS sites. The lifetimes of these systems have varied from one year on the short end to still in operation on the long end. Due to the unpredictability of the weather, USCG MLCPAC TE-3 will not be pursuing the further use of wind power in the immediate future. [17]

E. PROPANE GENERATORS

1. General

There are two propane generators at Robert Barron and Duke Island. Each generator consists of an engine with a governor, a three-phase alternator with a transformer, a diode rectifier, and a field exciter. The engine is a Lister Alpha Series LPWG2A070. The alternator is a Stamford BCA164E16311. [18]

2. Lister Alpha Series Engine

The Lister engine contains two cylinders and is spark fired. The governor is set to regulate propane consumption to maintain 1800 rpm. At 1800 rpm with a 75% load, the engine's rated fuel consumption is 37 cubic feet of propane per hour. Equation (2.1) illustrates how this value is converted to gallons per hour. [19]

$$\frac{37\,ft^3}{hr} \times \frac{2588\,BTU}{ft^3} \times \frac{gal}{91547\,BTU} = \frac{1.05\,gal}{hr} \tag{2.1}$$

The theoretical fuel consumption value, 1.05 gal/hr, is close to the estimate, 1.1 gal/hr, provided by USCG MLCPAC TE-3 and the vendor. Table (2-4) lists propane fuel information for Robert Barron and Duke Island.

The propane tanks at each site are only refueled to 80% of capacity for safety and environmental reasons as indicted in Table (2-4). These sites are normally only refueled during the summer. To ensure there is enough propane to run the generators, the sites are refueled when the tank gauges indicate there is at least a full year left of fuel. The amount of time the engines can run prior to the tanks being empty is also listed in Table (2-4). These values require that every gallon be used at each site. The values also assume the fuel consumption rate shown in Table (2-4). The total engine hours available at each site is achieved by alternately using the generator units; that is, only one generator unit is operated at a given time. [7], [17]

	Robert Barron	**Duke Island**
Capacity of Propane Tank	500 gal	500 gal
Number of Tanks	7	5
Maximum Site Capacity	3,500 gal	2,500 gal
Site Propane Cap. (80%)	2,800 gal	2,000 gal
Eng. Hours @ 1.1 gal/h	2545.5	1818.2
Eng. Hours @ 1.05 gal/h	2666.7	1904.8

Table 2-4. Propane Fuel and Run-Time Breakdown.

3. Stamford Alternator

The alternator contains a three-phase, four-wire, 120/208 V, 60 Hz, 7 kW synchronous machine with a nominal 0.7 power factor. The generator converts the mechanical power of the engine into electrical power. Next, a 12 KVA transformer steps the output from 208/120 VAC to 23/13.3 VAC. A 3-phase bridge rectifier then converts the voltage to DC. The Mechron system adjusts the generator exciter settings to control the field winding current to achieve the nominal load bus voltage of 24 VDC. [20]

F. MECHRON CONTROLLER

The Mechron controller employs a rotary battery system (RBS) to operate the propane generators that provide the electrical power necessary to charge the battery bank. There are over 30 RBS configuration settings. Table (2-5) displays the settings that are most important to this thesis.

The Low Battery Call to Start Level is designed to start one of the generators when the system voltage is at or below 23.8 VDC. The Normal Output Voltage Level ensures that the system voltage will not exceed 28.6 VDC (2.38 VPC) when a generator is charging the battery bank. The Finish Charging Current Level is set to de-energize a generator when the sensed current has dropped to 50 A. To compensate for temperature variation, the temperature compensation is set to 5.0 mV/°C. Therefore, as the ambient temperature in the generator building (where the batteries are stored) changes, the voltage settings are modified to ensure that DOD and the percent recharge of the batteries remain consistent. Equation (2.2) illustrates the temperature compensation procedure for a low battery call to start at a temperature of 15°C. As temperature decreases the voltage adjustment is added to the original value. Therefore, to maintain a 60% DOD at 15°C the battery voltage setting must be increased by 0.05 V to 23.85 V.

$$23.8V + 5\frac{mV}{^{\circ}C} \times \frac{1V}{1000mV} \times \left(25^{\circ}C - 15^{\circ}C\right) = 23.85V \tag{2.2}$$

The low temperature call to start level energizes a generator when the temperature inside the generator buildings drops to 5°C. [21]

Parameters	Value
Low Battery Call to Start Level	23.8 VDC
Normal Output Voltage Level	28.6 VDC
Finish Charging Current Level	50 ADC
Temperature Compensation	5.0 mV/°C
Low Temperature Call to Start Level	5°C

Table 2-5. RBS Configuration Settings From [21].

The Low Battery Call to Start Level and the Finish Charging Current Level were nominally chosen as a compromise between fuel consumption and battery life. In Chapter IV, these values are scrutinized and an algorithm is provided to produce optimal values for different loads.

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III. BATTERY FUNDAMENTALS

A. SECONDARY BATTERY SELECTION

Primary batteries provide electrical power at an approximate nominal voltage and can only be discharged once. Alkaline batteries are an example of a primary battery. These batteries are often used with consumer electronics. Since they cannot be recharged, primary batteries are poor candidates for use in a hybrid system requiring electrical power storage. Secondary batteries provide electrical power at a nominal voltage and can be repeatedly discharged and recharged without damage. As such, secondary batteries are excellent candidates for use in hybrid power applications. [22]

There are five major rechargeable battery systems: nickel-cadmium, nickel-iron, nickel-hydride, lithium, and lead-acid. The two most popular battery choices for use in hybrid power systems are nickel-cadmium and lead-acid. Lead-acid batteries are generally selected over nickel-cadmium because they cost one-fourth to one-third less than nickel-cadmium batteries. [22]

B. LEAD-ACID BATTERY CHEMISTRY

In a basic lead-acid battery, there is a positive plate made of PbO_2 and a negative plate made of sponge Pb both immersed in an H_2SO_4 electrolyte. The following overall reaction occurs. [22]

$$PbO_2 + Pb + 2H_2SO_4 \Leftrightarrow 2PbSO_4 + 2H_2O \tag{3.1}$$

The materials in the left half of the equation are produced when the battery is charged. The materials in the right half of the equation are produced when the battery is discharged. As shown in Equation (3.1), lead dioxide at the anode and sponge lead at the cathode react with sulfuric acid during discharge to form lead sulfate and water. During charging, this reaction reverses causing the lead sulfate on the electrodes to convert back to the original reagents. Unfortunately, this chemical reaction does not illustrate the production of current. By viewing the positive and negative plate reactions separately, it is apparent how current is produced. The following reaction takes place at the positive plate. [22]

$$PbO_2 + 3H^+ + HSO_4^- + 2e^- \Leftrightarrow PbSO_4 + 2H_2O \tag{3.2}$$

As before and with Equations (3.2) and (3.3), the reagents in the left half of the equation react to produce the materials in the right half of the equation during discharge. At the anode during discharge, lead dioxide reacts with positive hydrogen ions, negative hydrogen sulfate ions and two electrons to produce lead sulfate and water. At the cathode during discharge, as indicated by Equation (3.3), sponge lead and negative hydrogen sulfate ions react to produce lead sulfate, positive hydrogen ions and two electrons. The hydrogen ions carry the current from the anode to the cathode. The following reaction takes place at the negative plate. [22]

$$Pb + HSO_4^- \Leftrightarrow PbSO_4 + H^+ + 2e^- \tag{3.3}$$

During the charging process, the reagents in the right half of Equations (3.2) and (3.3) react to produce the materials in the left half of these same equations. As with the discharge process, the positive hydrogen ions carry the current. However, during the charging process, current is carried from the cathode to the anode. [22]

C. ABSOLYTE IIP CONSTRUCTION

The Absolyte IIP varies slightly from the lead-acid battery discussed in the previous section. The Absolyte IIP is a sealed VRLA battery with an absorbent glass mat (AGM) separator to act as the electrolyte retainer. The positive plate is constructed from a patented MFX grid alloy while the negative plate is a lead calcium grid alloy. The safety vent is rated at six pounds per square inch and is self re-sealing. In this type of battery water cannot be added.

D. LEAD-ACID BATTERY CAPACITY FUNDAMENTALS

1. General

A fully charged lead-acid battery cell roughly has a charge of two volts. As the battery is used (discharged), its voltage will decrease. The rate of voltage decrease increases as the current drawn by the load increases. Since the current drawn by the loads at Robert Barron and Duke Island is small, the corresponding rate of voltage decrease is low.

The nominal (rated) capacity is "…the maximum Ah a fully-charged battery can deliver under specified conditions." The nominal capacity varies depending on the current drawn during discharge, the temperature, and the final voltage of the battery. [22]

2. Discharge Current

Manufacturers typically specify the rate at which their stated capacity is valid. For example, the Absolyte IIP 3-100A17 is rated for 800 AH at the eight-hour rate [16]. This means that 100 A can be drawn for eight hours before the battery is at 100% DOD. The same battery also is rated for 1065 AH at the 100-hour rate [13]. This means that 10.65 A can be drawn for 100 hours before the battery is at 100% DOD. When two batteries are placed in parallel the combined capacity is twice the individual capacities. Additionally, the current drawn from each battery is half of what it would be if only one battery were present. Since Robert Barron and Duke Island have two strings in parallel, the total capacity at the 100-hour rate is 2030 AH. This means that the battery banks are capable of delivering 20.3 A for 100 hours before 100% DOD.

"The lower available capacity at higher currents is due to internal resistance and less uniform discharge of the active materials." The batteries at Robert Barron and Duke Island have an increased capacity at lower currents related to the amount of electrolyte in the cell. "If there is a large reserve of acid, which takes part in the discharge reaction, then at low currents fresh acid can diffuse to the area between the plates and allow more reaction of the active materials." [22]

3. End Voltage

The end (final) voltage of a particular battery is an arbitrary value chosen by the user that corresponds to a specific DOD. The end voltage is a set point where the battery voltage will be when discharging has stopped and charging commences. For example, with the Absolyte IIP 3-100A17, a 60% DOD corresponds to a 1.98 VPC end voltage when operating at the 100-hour rate. The end voltage will affect the relative capacity of the battery when its chosen value differs from the manufacturer's stated end voltage associated with the battery's nominal capacity. Even though the Absolyte IIP 3-100A17 is rated for 1065 AH at the 100-hour rate, 10.65 A will only be drawn until the end voltage reaches 1.98 VPC [13], [15]. Since 1.98 VPC occurs before 1.75 VPC (100%

DOD), the number of Amp-Hours provided by the time 1.98 VPC is reached is less than the Amp-Hours provided when 100% DOD is reached.

The end voltage affects where the discharge curve stops, not the shape of the curve. In Figure (2-2), the 1.4 A/pos curve illustrates how the Absolyte IIP 3-100A17 battery discharges. If 1.98 VPC were selected as the end voltage, the effect would be to simply project a horizontal line out from 1.98 VPC on the y-axis and intersect the 1.4 A/pos curve. At the intersection point there is an associated time of 61.2 hours. Taking this time and dividing by 102 hours yields 0.6 or 60% DOD. Therefore the relative capacity of this 1065 AH battery is 639 AH (the product of 0.6 and 1065 AH) when the end voltage is 1.98 VPC. Figure (3-1) pictures the complex relationship among capacity, end voltage, discharge rate, and time.

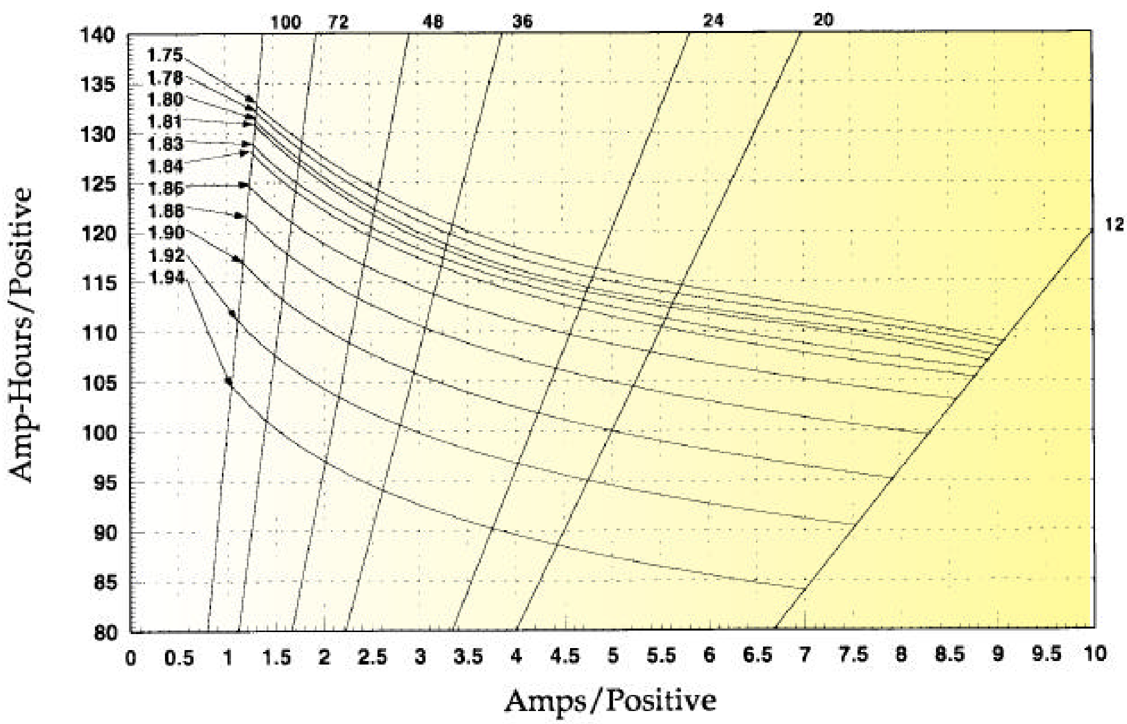

Figure 3-1. Absolyte IIP Performance Curves at 25°C From [13].

In Figure (3-1), the numbers 100, 72, 48, 36, 24, 20, and 12 and their associated lines in the plot represent times in hours. The set of labeled curves in the plot correspond to certain end voltages in VPC. The left-hand axis is battery capacity given in Amp-

Hours per positive plate, while the bottom axis is discharge rate given in Amps per positive plate. To determine the 100% DOD (1.75 VPC) capacity at the 100-hour rate, multiply 133.125 AH/pos (capacity at 1.75 VPC and the intersection of the 100-hour line) by 8 positive plates. The result is 1065 AH or the rated capacity at the 100-hour rate.

4. Temperature

The temperature of the cell affects the battery's relative capacity. The Absolyte IIP varies in relative capacity from 72% at 32°F to 103% at 86°F as shown in Figure (3-2) [13]. In the previous discussions on capacity, the temperature was assumed to be 77°F (25°C) as stated in the Absolyte IIP performance specifications [13]. Although at temperatures greater than 77°F the battery capacity increases, for every 10°C above 25°C the number of cycles a battery is capable of producing at any DOD is halved [13]. The temperature where the batteries are stored at Duke Island and Robert Barron fluctuates between 59°F and 80°F (thus the capacity varies between 90% and 101%) [17].

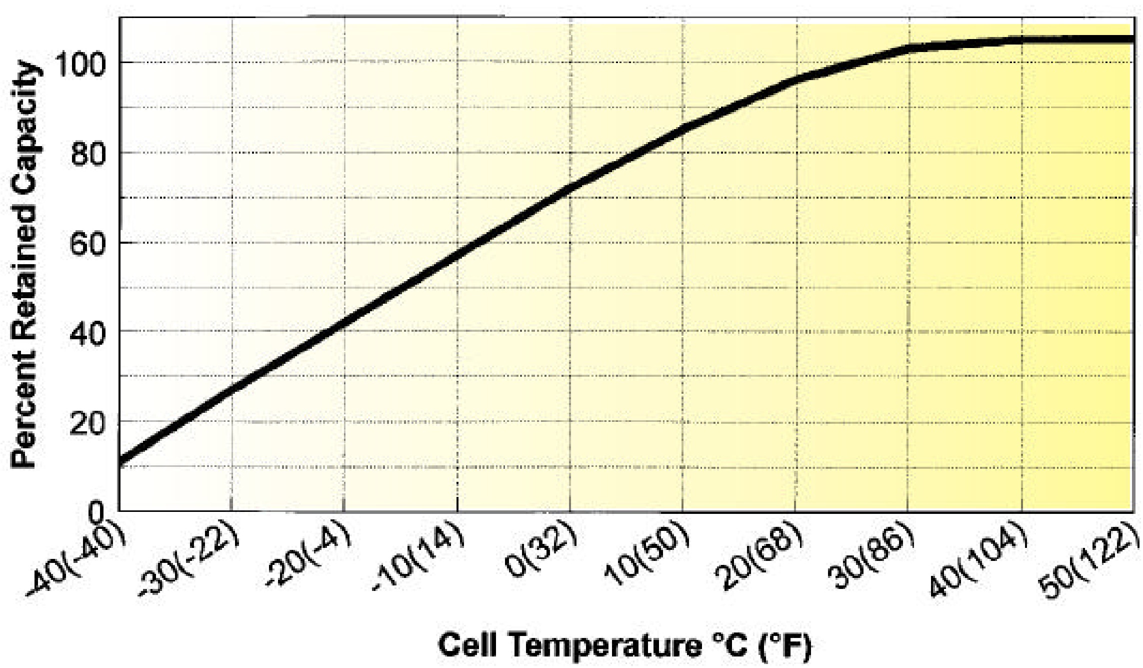

Figure 3-2. Capacity Available Vs. Cell Temperature From [13].

E. LEAD-ACID BATTERY LIFETIME

1. Cycling

Each time a battery is discharged and then subsequently recharged, a cycle is counted. The repetition of this process is called cycling. In deep cycling, a battery is discharged to at least 50% DOD but not more than 80% DOD. In shallow cycling, a battery is typically discharged between 0 and 20% DOD. Moderate cycling is classified between 20 and 50% DOD. [22]

The process of discharging and charging is accompanied by "…chemical changes in the active materials of the electrodes…." leading to changes in volume. As this process repeats itself, a portion of the active material may become "…isolated from the current pathway, either because it physically drops off, or because an insulating layer builds up around it." This chemical process reduces the battery's capacity over time. Cycle life is the number of cycles that a battery goes through before its capacity has been reduced to a certain level below its initial capacity. [22]

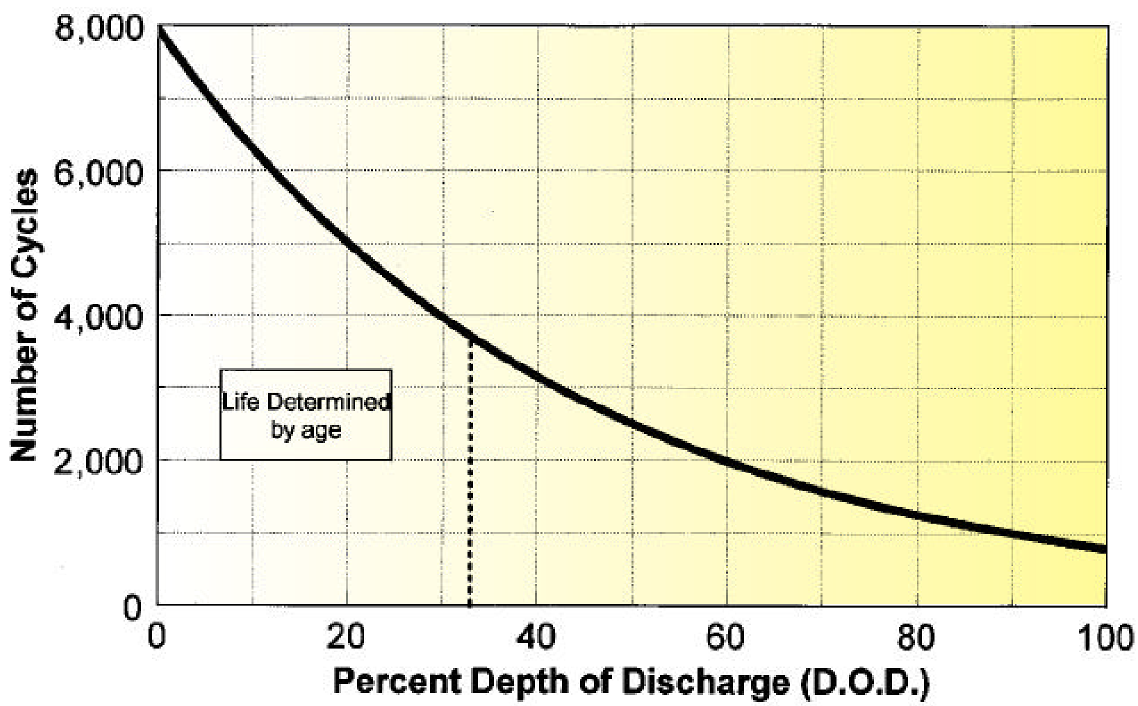

Figure 3-3. Cycles Available Vs. Percent DOD at 25°C From [13].

Battery manufacturers typically list the lifetime of their batteries by listing how many cycles the battery can deliver at various depths of discharge. As the capacity of a battery decreases because of temperature or other effects, the frequency of battery cycling will increase to meet the same needs of the load. Figure (3-3) displays the number of cycles that the Absolyte IIP can deliver at 77°F as the DOD changes. As illustrated in Figure (3-3), at 60% DOD, the number of cycles that can be delivered in a lifetime is 2000. At 60% DOD and 1.46 A of finish current (applies to Robert Barron), the recharge time for the batteries is estimated from Figure (2-3) to be roughly 7 hours. Therefore, the time of one cycle, in hours, is 57.2 (discharge time) plus 7 (charging time), which is equivalent to 64.2 hours. The number of cycles occurring in one year is 8760 (hours in one year) divided by 64.2, which is equivalent to 136.4 cycles. Therefore, the number of years before the batteries are no longer able to support the load is 14.7 (2000 divided by 136.4). The value of 14.7 years, assumes a constant temperature of 77°F and that no power is supplied by the photovoltaic arrays.

2. Battery Age

The section of the curve in Figure (3-3) from 0 to 32% DOD is governed by the age of the battery, not DOD. Aging occurs due to "…internal corrosion processes that proceed continuously at a low rate." These processes reduce the capacity of the battery in a similar manner to the chemical processes that occur during cycling. When a battery is not discharged much, it is considered to be on float duty where the battery is charged by a voltage that remains at a suitable level during normal operation. The float service lifetime is the value given to batteries that operate in this manner. The float service lifetime is heavily dependent upon temperature. Since USCG MLCPAC TE-3 does not operate site batteries is this manner, battery age is not an important factor in determining lifetime. [22]

3. Cell Reversal

One of the reasons that it is not recommended to discharge lead-acid batteries below 80% DOD is cell reversal. Since lead-acid cells only provide two volts, it is necessary to connect these cells in series to increase the voltage. The Absolyte IIP 3-100A17 battery is comprised of three cells for a total of six volts. To provide the required 24 VDC for the loads at Robert Barron and Duke, four Absolyte batteries are required to be in series. The SOC of each cell in series may not be the same due to ageing or even temperature variation. In deep discharge cycles past 80% some cells may become 100% discharged prior to others leading to cell reversal. As the discharging continues, these 100% discharged cells will become reversed in voltage. Reversed in voltage means that the positive plate is negative and the negative plate is positive. As current is forced through the cell, the plates will be damaged. Additionally, gas pressure will build up rapidly and electrolyte will be lost. In a sealed battery, it is possible that a cell may explode. [22]

4. Gassing

As indicated in Figure (2-3), during the initial stage of charging, the charge current is high and constant. During this part of the charging process, conversion efficiency is nearly 100%. "As the battery voltage rises during this phase, it reaches a point where some of the current is consumed by gassing, which is the electrolytic decomposition of some of the water into hydrogen and oxygen…." In a VRLA battery such as the Absolyte IIP, both the oxygen and hydrogen recombine if the rate of their production is below a certain level. During this phase of charging, it is necessary to reduce the charge current to ensure the rate of production of oxygen and hydrogen is below the potential rate of recombination. Maintaining the voltage of the cell at a constant value regulates the current. As this gassing takes place, the efficiency of the charging process deteriorates. If the gassing rate is too high, electrolyte is sprayed through the valves, which reduces battery capacity. [22]

5. Equalizing Charge

For many applications, ageing at different rates and routine cycling can lead to different SOCs for the cells in a battery bank. To bring the cell members back to the same SOC, an equalizing charge is typically used. To perform an equalizing charge, a larger than normal charging current is applied to charge the weaker cells back up to the same charge as the stronger cells [22]. Due to its unique construction, the Absolyte IIP 3-100A17 is normally not required to undergo equalization unless it has been operated outside stated parameters [23].

6. Stratification

Stratification occurs when there is a higher concentration of sulfuric acid toward the bottom of the battery than the top. Stratification can reduce the capacity of a lead-acid battery. During an equalization charge, the gas bubbles produced will evenly redistribute the sulphuric acid throughout the battery. One of the qualities of a VRLA AGM battery like the Absolyte IIP 3-100A17 is that it minimizes stratification because of the way it is constructed so the need for the equalization process to eliminate stratification is reduced. [22]

7. Sulfation

When a battery remains at a deep discharge for an extended period of time, "…lead sulfate crystals initially formed during recharge may re-crystallize into larger pieces which are not easy to recharge…." This sulfation can result in a permanent reduction of battery capacity. Figure (3-4) illustrates sulfation. [22]

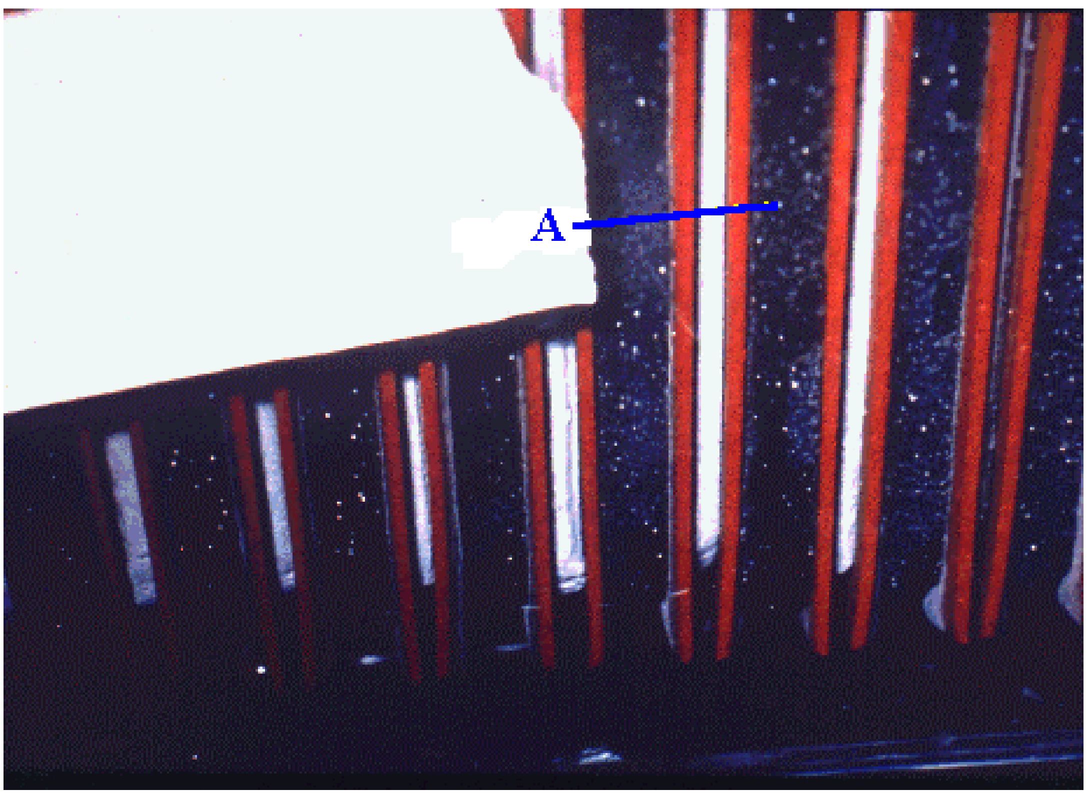

Figure 3-4. Sulfation of a lead-acid battery From [24].

In Figure (3-4) "A" points to one of the many "…large white sulfate crystals…" formed on the positive plates of the pictured battery. This battery is so severely affected that the damage done is permanent. To erase the effects of sulfation, it is necessary to completely recharge a battery. If a battery is continually charged to only 90% SOC, sulfation occurs causing a permanent 10% loss of capacity. [24]

F. ALTERNATIVE BATTERY TECHNOLOGIES

1. General

There are several types of batteries available for consumer use in systems that require multiple cycles. Determining which battery should be used for a particular application requires substantial knowledge of the power requirements for the application and the strengths and weaknesses of the potential battery candidates. This section discusses the advantages and disadvantages associated with nickel-cadmium, nickel-metal hydride, lithium ion, and lithium polymer batteries.

2. Nickel-Cadmium

Nickel-Cadmium (Ni-Cd) batteries have not been widely used in many applications due to their high cost. However, despite the high cost associated with Ni-Cd batteries, there are notable advantages they have over lead-acid batteries.

As earlier stated, lead-acid batteries lose half their life for every 10°C above 25°C that they are operated. Ni-Cd batteries only lose 20% of their life under the same temperature considerations [25]. Due to the temperature benefits of a Ni-Cd battery, it may be more economical to use a Ni-Cd battery at extremely high temperatures than a lead-acid battery.

The other major advantage that a Ni-Cd battery has over the lead-acid battery is a lack of internal corrosion. The "…structural components of lead-acid battery positive plates degrade over time through a corrosion process…." Ni-Cd batteries protect the internal steel hardware through the use of an alkaline electrolyte. The result of this protection allows "…thin-plate high-performance designs to be built without sacrificing life expectancy." The energy density and cell voltage characteristics of the various battery types are listed in Table (3-1). [25]

3. Nickel-Metal Hydride

Nickel-Metal Hydride (Ni-MH) batteries, though chemically similar to Ni-Cd batteries, store a much greater amount of energy in a smaller area than Ni-Cd batteries. Ni-MH batteries are particularly useful for applications short on available equipment storage space. Like a Ni-Cd battery, Ni-MH batteries are less temperature sensitive than lead-acid batteries, however, not to the same extent as Ni-Cd batteries. Despite the energy storage advantages over a Ni-Cd battery, a Ni-MH battery is more expensive than a Ni-Cd battery and does not perform as well at high temperatures. For these reasons, a Ni-MH battery is not a suitable substitution for a Ni-Cd battery at high temperatures. [25]

4. Lithium Ion

Lithium Ion (Li-ion) batteries perform almost identically at high temperatures as they do at 25°C. Additionally, as indicated in Table (3-1), their energy storage density is between four to six times greater than lead-acid batteries. Li-ion batteries are almost 100% efficient during cycling. The high efficiency is due to the absence of water in the Li-ion system. Since there is no water, electrolysis and gassing cannot occur in a Li-ion battery. The major drawback to a Li-ion battery is its high cost. The Li-ion battery is much more expensive than a Ni-MH battery, which is more expensive than a Ni-Cd battery, which is more expensive than a lead-acid battery.

5. Lithium Polymer

The dry polymer Lithium polymer (Li-polymer) batteries consist of a "…solid polymer that encapsulates the electrodes." Li-polymer batteries must be operated at temperatures between 60°C and 80°C or there will not be adequate conductivity. The technology of the Li-polymer battery is still under development. However, there is reason to believe that this battery will outperform the Li-ion battery in the future. [25]

6. Conclusion

There are many choices for energy storage. The battery technologies previously mentioned represent a fraction of the options available for energy storage. Each power application has unique requirements for energy. Table (3-1) provides a basic summary of the battery technologies previously discussed.

	Cell Voltage	**Energy Density (Wh/liter)**
Vented lead-acid	2.0 V	25
Vented Ni-Cd	1.2 V	27
VRLA	2.0 V	54
Ni-MH	1.2 V	135
Li-ion	3.6 V	230
Li-polymer	2.5 V	135

Table 3-1. Energy Densities for Alternative Battery Technologies From [26].

IV. MECHRON CONTROL SYSTEM

A. HARDWARE

The Mechron RBS Controller monitors the power system's main bus voltage and current at each site. As earlier stated, when the voltage drops below a set threshold, the controller sends a signal to start the generator. Once the generator starts, the controller adjusts the terminal quantities by manipulating the current in the rotating field winding. The current is varied by controlling the field voltage using a pulse-width-modulation (PWM) amplifier. The relevant signal flow is shown in Figure (4-1). [27]

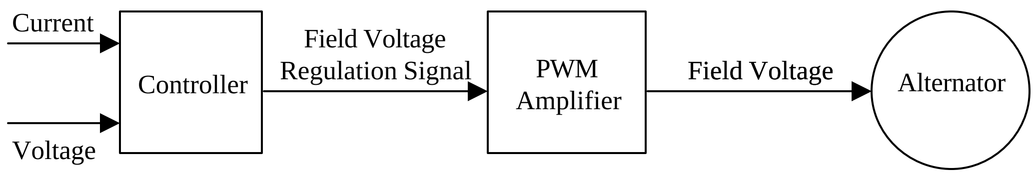

Figure 4-1. Alternator Control Signal Flow After [27].

Two motherboards, the processor and slave, carry out the control process. The input to the controller has 10-bit resolution while the output is 8-bit. The output signal sets the duty cycle of the PWM amplifier that, in turn, applies the field voltage. [27]

B. SOFTWARE CONTROL ALGORITHM

The controller employs fuzzy logic to control the steady-state, transient, and sinusoidal ringing components of the current and voltage. During the initial charging phase, the current is constant at 160 A (Figure (2-3)). Throughout this initial phase, the controller regulates the current at 160 A while the voltage steadily increases until it reaches 28.6 V. Once the voltage has reached 28.6 V, the controller allows the current to exponentially decrease by maintaining a constant voltage (Figure (2-3)). [27]

In order to maintain the voltage or current within 2% of their expected values, the controller modifies the PWM amplifier duty cycle based on the effects of the three components: steady-state, transient, and ringing. The steady-state component is the value specified by the user: in this case 160 A or 28.6 V. The other two components represent undesirable effects present during various load conditions. The transient component typically occurs when there is a load spike, such as when a radio is keyed. The ringing component occurs at light load, toward the end of the charging process when generator current is small. [27]

There are three fuzzy control factory settings. The highest setting, 40, applies the appropriate response when there is a "large" out of bounds from expected stability. The middle setting, 5, applies when there is a "medium" out of bounds from expected stability. The lowest setting, 1, applies when actual conditions are within expected stability boundaries. An out of bounds occurs when sensed voltage or current is a "large" or "medium" amount outside of set thresholds (nominally selected to be 2%). Additional information on fuzzy logic mathematics and applications is available in the literature [28]. [27]

C. DATA ANALYSIS

1. General

The Robert Barron and Duke Island sites are polled every 16 minutes to record a variety of data including voltage, current, temperature, and generator status. To become familiar with the past operations of each site, data was collected electronically via the website mentioned in Chapter II (http://www.ktn.net/~ndsemc) and transferred to databases for the year 2001.

2. Data Manipulation

a. General

The data is separated by month into 12 databases, each containing data for both Robert Barron and Duke Island. The voltage and load current (not equal to the actual load current as indicated in Chapter II) data points are plotted separately over the course of a month for the entire year.

b. Duke Island

Figure (4-2) illustrates a plot of voltages during January 2001 at Duke Island.

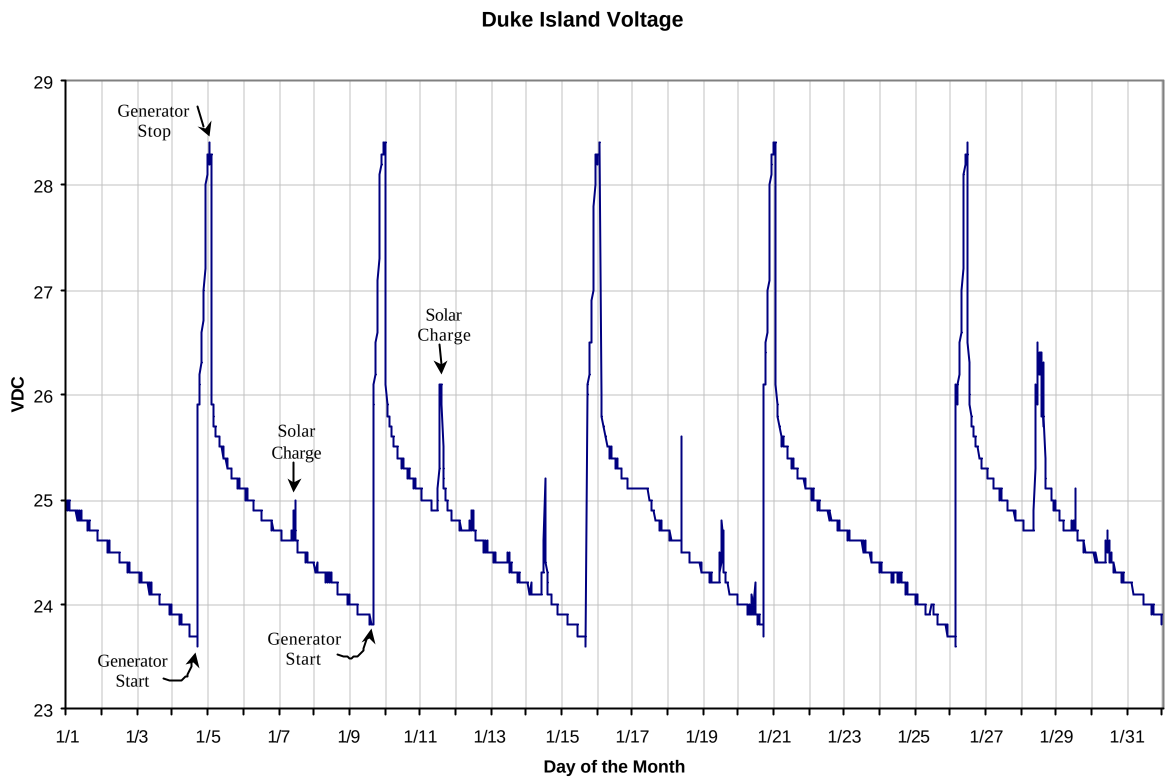

Figure 4-2. Duke Island VDC for January 2001.

As shown in Figure (4-2), the month begins with the batteries discharging from a local starting point near 25 VDC. The discharge process continues until the voltage is below 24 VDC. At this point, one of the propane generators starts, initiating the charging process. The charging process continues until the voltage is above 28 VDC, ceasing generator operation. The discharge process then initiates and continues until there is a brief interruption caused by increased voltage produced by the solar arrays. This power charges the batteries, raising the voltage to about 25 VDC before the solar energy dissipates. The batteries continue discharging until the monitoring and control system triggers the other generator (the one that did not start during the previous charging cycle) starts, commencing the charging process. The cycling process (generator start to generator start) continues throughout the month with minor variations in the discharge process due to the influence of solar power.

Duke Island Data for Calendar Year 2001					
	1st Qtr	2nd Qtr	3rd Qtr	4th Qtr	Year
Total Generator Run-Time From Charging (hrs)	105.59	54.41	91.73	158.4	410.13
Total Miscellaneous Generator Run-Time (hrs)	0.80	0	0	0	0.80
Total Number of Generator Charging Processes	13	7	12	36	68
Average Charging Time per Cycle (hrs)	8.12	7.77	7.64	4.40	6.03
Total Discharging Time With Solar (hrs)	2054.41	2129.59	2116.27	2049.60	8349.87
Avg. Discharging Time per Cycle Without Solar (hrs)	120	96	96	53	77.82
Total Discharging Time Without Solar (hrs)	1560	672	1152	1908	5291.76
Average Discharging Time per Cycle With Solar (hrs)	158.03	304.23	176.36	56.93	122.79
Average Added Time to Discharging Process per Cycle Due to Solar (hrs)	38.03	208.23	80.36	3.93	44.97
Total Number of Battery Cycles Due to Solar	54	91	70	47	262
Average DOD Prior to Solar Recharge	29%	25%	26%	22%	26%

Table 4-1. Duke Island Data by Quarter for 2001.

Although Figure (4-2) provides an overall depiction of the operation of the Duke Island site during January 2001, it does not offer fine enough details to determine accurate durations associated with the charging, discharging, and solar processes. Through a combination of database values and the overall picture provided by plots such as the one depicted in Figure (4-2), the lengths of time for each of the aforementioned processes were evaluated and are recorded in Table (4-1).

In this thesis, each quarter represents a three-month period. The first quarter begins on the first day of January and ends on the last day of March. Subsequent quarters begin April 1, July 1, and October 1.

In Table (4-1), the Total Generator Run-Time From Charging is the number of hours the generators at Duke Island ran for the purposes of charging the batteries. In the first quarter, the generators charged the batteries for 105.59 hours. The Total Miscellaneous Generator Run-Time is the number of hours the generators ran for reasons other than charging the batteries (0.80 in the first quarter). The Total Number of Generator Charging Processes is the number of times the generators charged the batteries as prescribed by the generator settings discussed in Chapter II (13 times in the first quarter). The Average Charging Time per Cycle is the average number of hours the generators ran each time the batteries were charged ($\frac{105.59}{13} = 8.12$ hours in the first quarter). The Total Discharging Time With Solar is the summation of the number of hours in each Generator Stop to the following Generator Start period including time added by solar charging. The value is calculated by subtracting the Total Generator Run-Time From Charging away from the number of hours in the desired quarter (2054.41 hours in the first quarter). The Avg. Discharging Time Without Solar is average number of hours in each Generator Stop to the following Generator Start period excluding any time added from solar charging (120 hours in the first quarter). The Total Discharging Time Without Solar is the summation of the number of hours in each Generator Stop to the following Generator Start period excluding any time added from solar charging (1560 hours in the first quarter). The Average Discharging Time per Cycle With Solar is the average number of hours in each Generator Stop to the following Generator Start period including time added by solar charging (158.03 hours in the first quarter). The Average Added Time to Discharging Process per Cycle Due to Solar is the average number of hours added to the Avg. Discharging Time per Cycle Without Solar to account for solar charging (38.03 in the first quarter). The Total Number of Battery Cycles Due to Solar is the number of times a solar charge occurred during the period (54 in the first quarter). The Average DOD Prior to Solar Recharge is the average SOC the batteries were at when each solar charge commenced (29% DOD in the first quarter).

As demonstrated in Table (4-1), there is a quarterly variation with the values calculated in the different categories. This variation is mostly due to the solar fluctuation throughout the year. Figure (4-3) illustrates a plot of voltages at Duke Island during June 2001. During June, there are a significantly greater number of solar charging processes than in January. The major effect at Duke Island during months where there is a large amount of solar energy conversion is a decrease is the necessary amount of generator run-time. Additionally, the overall (including solar processes) average discharging time is also increased.

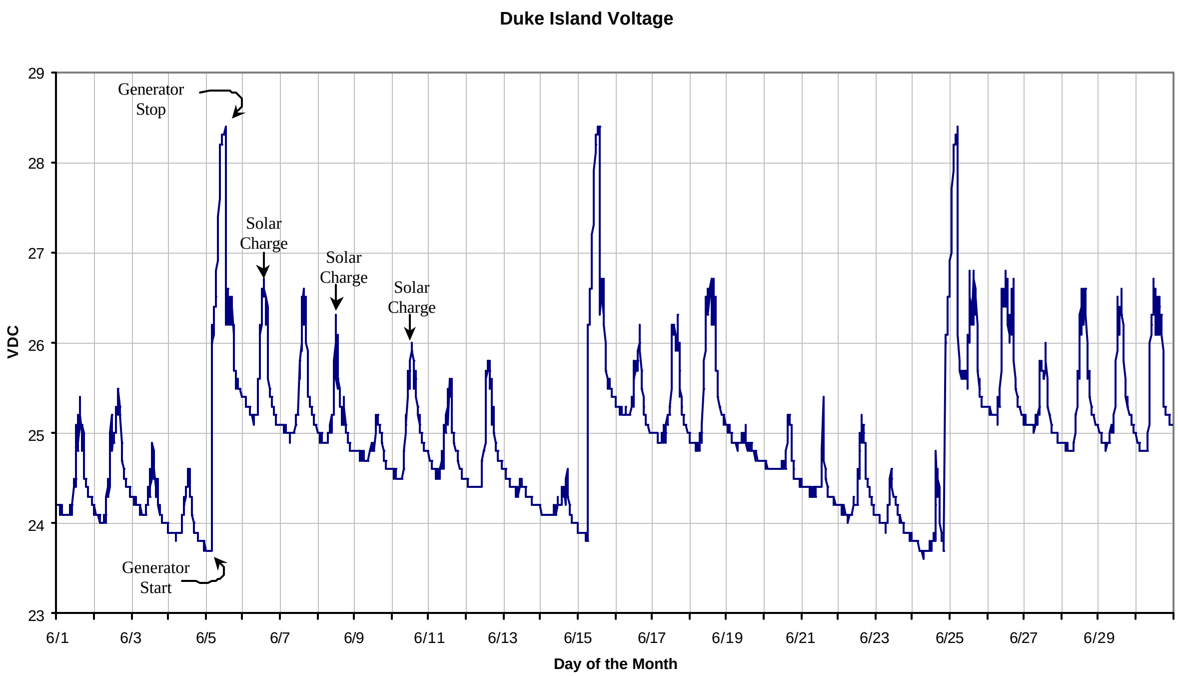

Figure 4-3. Duke Island VDC for June 2001.

In Figure (4-3), three of the many solar charging processes are labeled. Not surprisingly, the charging due to solar energy occurs during the middle of the day. It is also important to note that a generator only charges the batteries three times in June as compared with five times during the month of January 2001.

c. Robert Barron

Like the site at Duke Island, the site at Robert Barron receives its power from the sun, propane generators, and batteries. As a result, plots of voltage at Robert

Barron follow a similar characteristic pattern to the voltage plots from Duke Island. Figure (4-4) illustrates the time variation of voltage at Robert Barron during January of 2001.

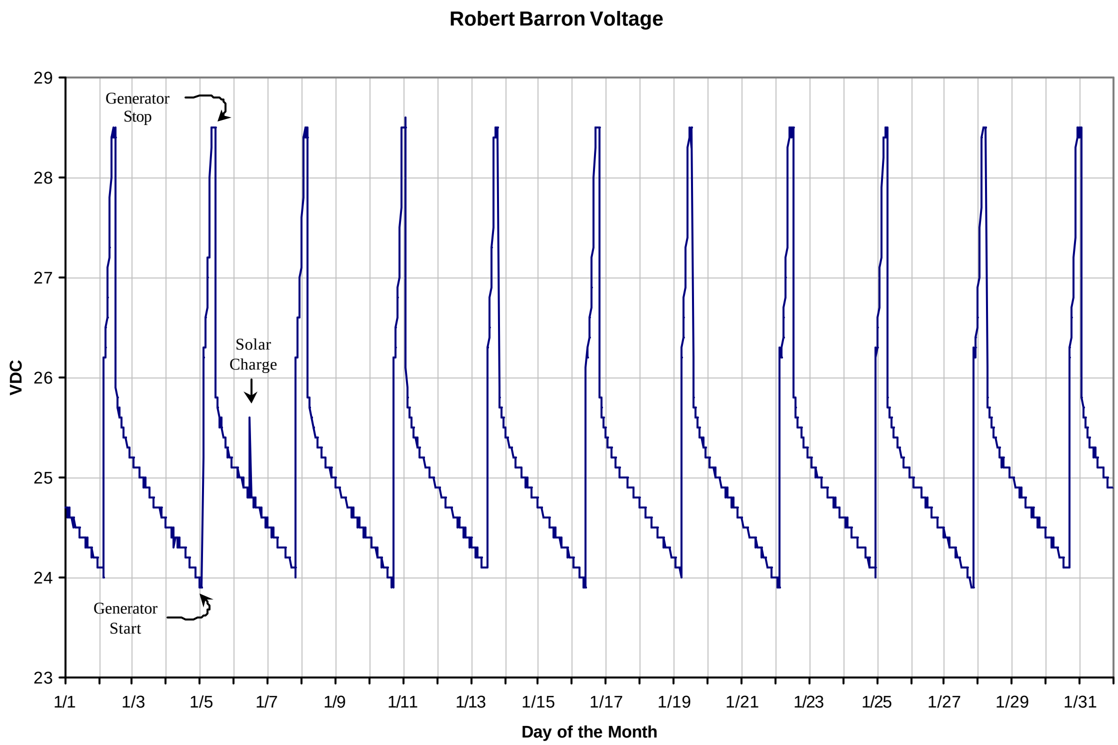

Figure 4-4. Robert Barron VDC for January 2001.

Figure (4-4) shows that the generators combined to charge the battery bank 11 times during the month of January at Robert Barron. The number of generator processes at Robert Barron is almost twice the number at Duke Island (six) during January 2001. The most significant reason for the increase in the number of cycles is the higher load current (also indicates a higher discharge rate) at Robert Barron as discussed in Chapter II. The associated time to a specified DOD at Robert Barron is shorter than the time at Duke Island because of the higher discharge rate at the Robert Barron site. A shorter discharge time leads to a greater number of generator cycles, especially when little or no power is provided by the photovoltaic arrays.

During the sunnier months at Robert Barron, a sizable amount of power is provided by the solar arrays. Figure (4-5) pictures the voltage at Robert Barron during the month of June 2001.

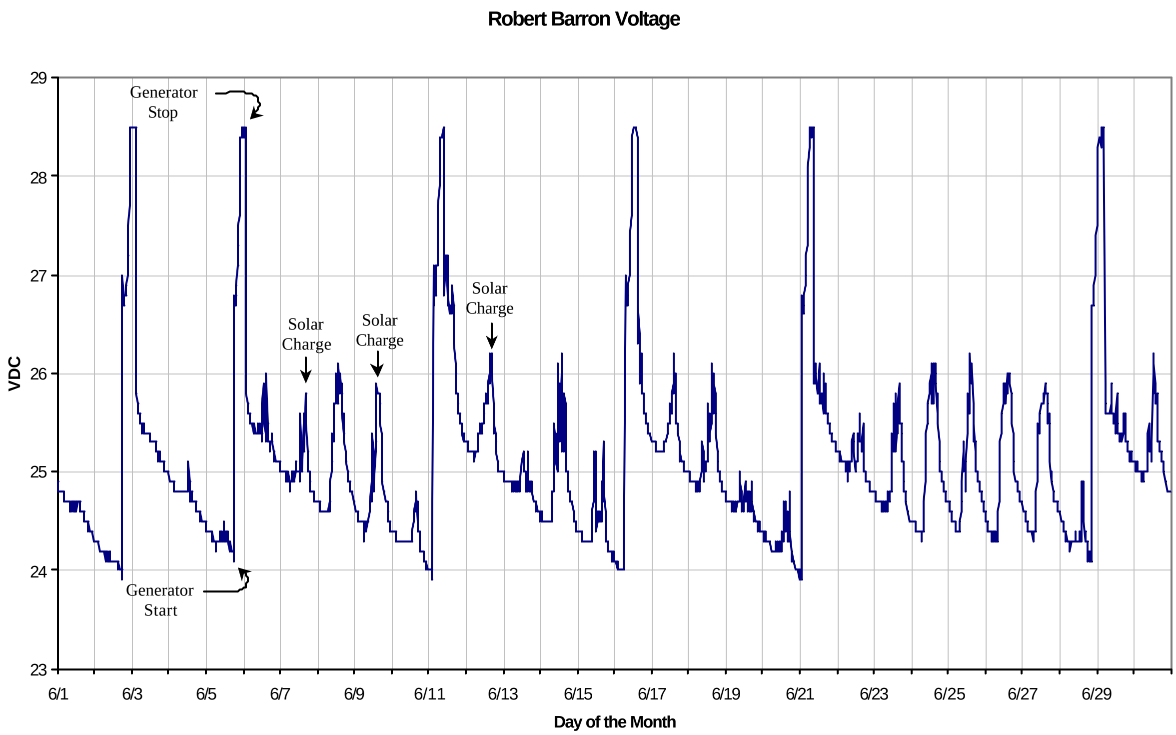

Figure 4-5. Robert Barron VDC for June 2001.

In Figure (4-5), the generator start, generator stop, and three of the many solar charging times are labeled. As compared with January 2001, there are almost half as many generator charging processes during June 2001.

As mentioned previously, it is difficult to accurately determine the duration of charging and discharging over a specified period of time from plots such as the one depicted in Figure (4-5). Therefore, it is necessary to use both numerical data along with plots to calculate certain values. Table (4-2) displays the characteristics of the site at Robert Barron throughout the four calendar quarters of 2001.

Robert Barron Data for Calendar Year 2001					
	1st Qtr	**2nd Qtr**	**3rd Qtr**	**4th Qtr**	**Year**
Total Generator Run-Time From Charging (hrs)	292.85	246.15	203.74	299.87	1042.61
Total Miscellaneous Generator Run-Time (hrs)	1.07	0	2.4	0	3.47
Total Number of Generator Charging Processes	58	41	25	35	159
Average Charging Time per Cycle (hrs)	5.05	6.00	8.15	8.57	6.56
Total Discharging Time With Solar (hrs)	1867.15	1937.85	2004.26	1908.13	7717.39
Avg. Discharging Time per Cycle Without Solar (hrs)	32	40	50	52	41.30
Total Discharging Time Without Solar (hrs)	1856	1640	1250	1820	6566
Average Discharging Time per Cycle With Solar (hrs)	32.19	47.26	80.17	54.52	48.54
Average Added Time to Discharging Process per Cycle Due to Solar (hrs)	0.19	7.26	30.17	2.52	7.24
Total Number of Battery Cycles Due to Solar	1	33	41	6	81
Average DOD Prior to Solar Recharge	18%	22%	22%	26%	22%

Table 4-2. Robert Barron Data by Quarter for 2001.

Solar power provides the greatest benefit during the third quarter of 2001. As shown in Table (4-2), during the summer months, solar power increases the average discharging time by 30.17 hours. The solar power during the third quarter results in fewer generator cycles and less generator run-time than during the rest of the year.

d. Load Current Data

The load current at Duke Island and Robert Barron varies throughout each month. Figure (4-6) shows how the load varies at Duke Island. The current fluctuates between 5 A and 6 A during most of January 2001. The occasional current spikes are a result of radios being keyed as mentioned in Chapter II.

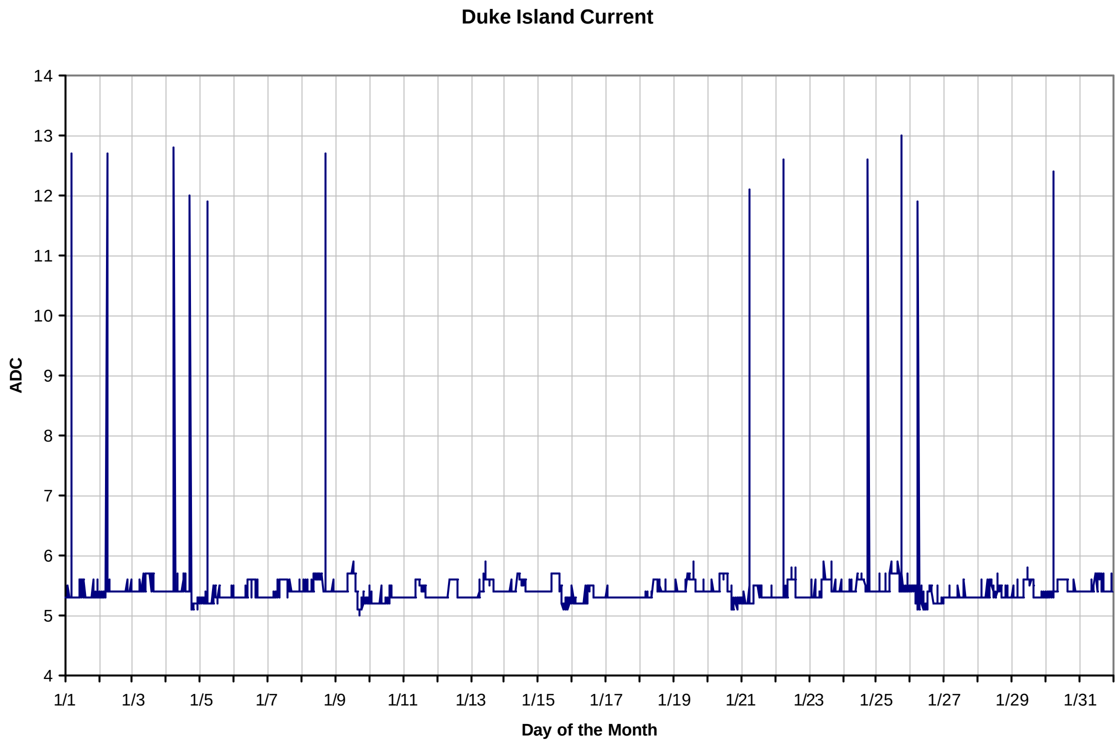

Figure 4-6. Duke Island Load for January 2001.

The load at Robert Barron varies during the month of January as shown in Figure (4-7). The majority of the time the load current fluctuates between 8 A and 10 A with occasional current spikes ranging from 12 A to 19 A. The current spikes, like those at Duke Island, are due to radios being keyed at the site.

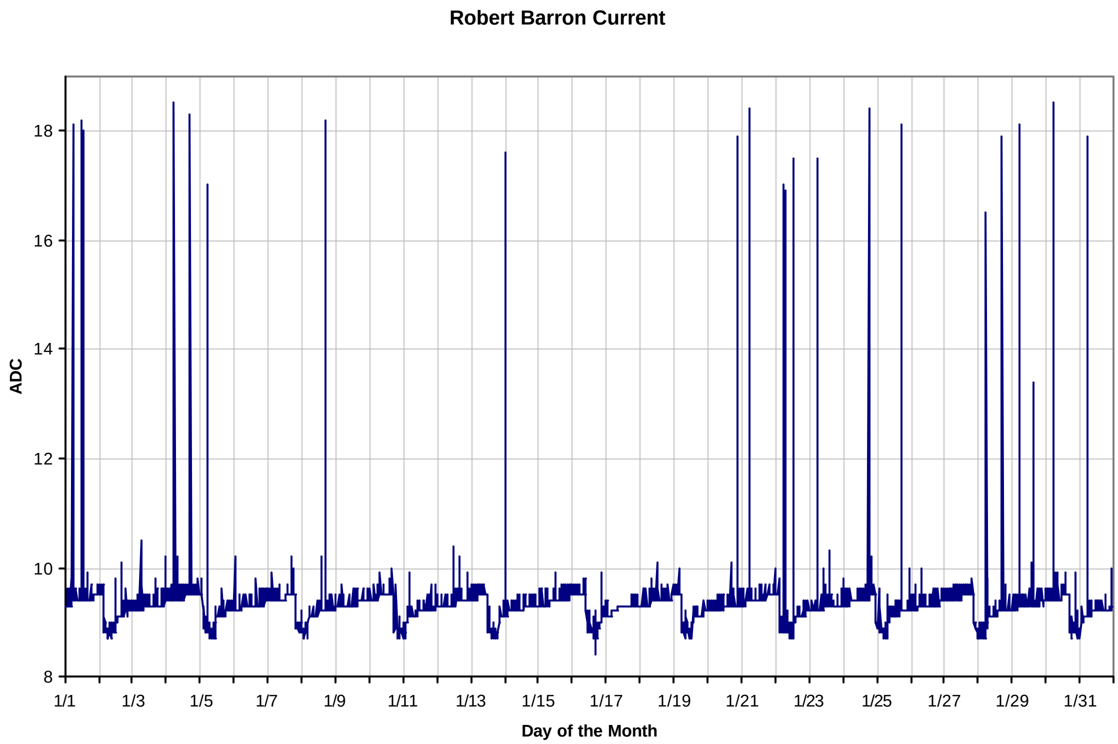

Figure 4-7. Robert Barron Load for January 2001.

D. SYSTEM OPTIMIZATION

1. General

To achieve the lowest possible costs associated with operating the equipment at Duke Island and Robert Barron, it is necessary to mathematically characterize the system providing power to the electronic equipment. A Microsoft Excel spreadsheet is used to simulate the operation of each site (an Excel guide is available under the help menu when the software program is active). The spreadsheet uses theoretical and empirical data to predict future site results. Additionally, a flowchart was created to illustrate the processes taking place in the spreadsheet.

2. Simulation Flowchart

The flowchart depicted in Figure (4-8) shows the logical flow that various inputs follow in the spreadsheet as they are processed to achieve the lowest cost. In the flowchart, there are different shapes to separate types of processes, data, and inputs. Trapezoids represent inputs entered by the user. Rectangles, squares, and ovals represent processes such as multiplication, addition, and division, to name a few. Parallelograms represent values generated within the spreadsheet by various processes. Diamonds represent decision points leading to one of two options.

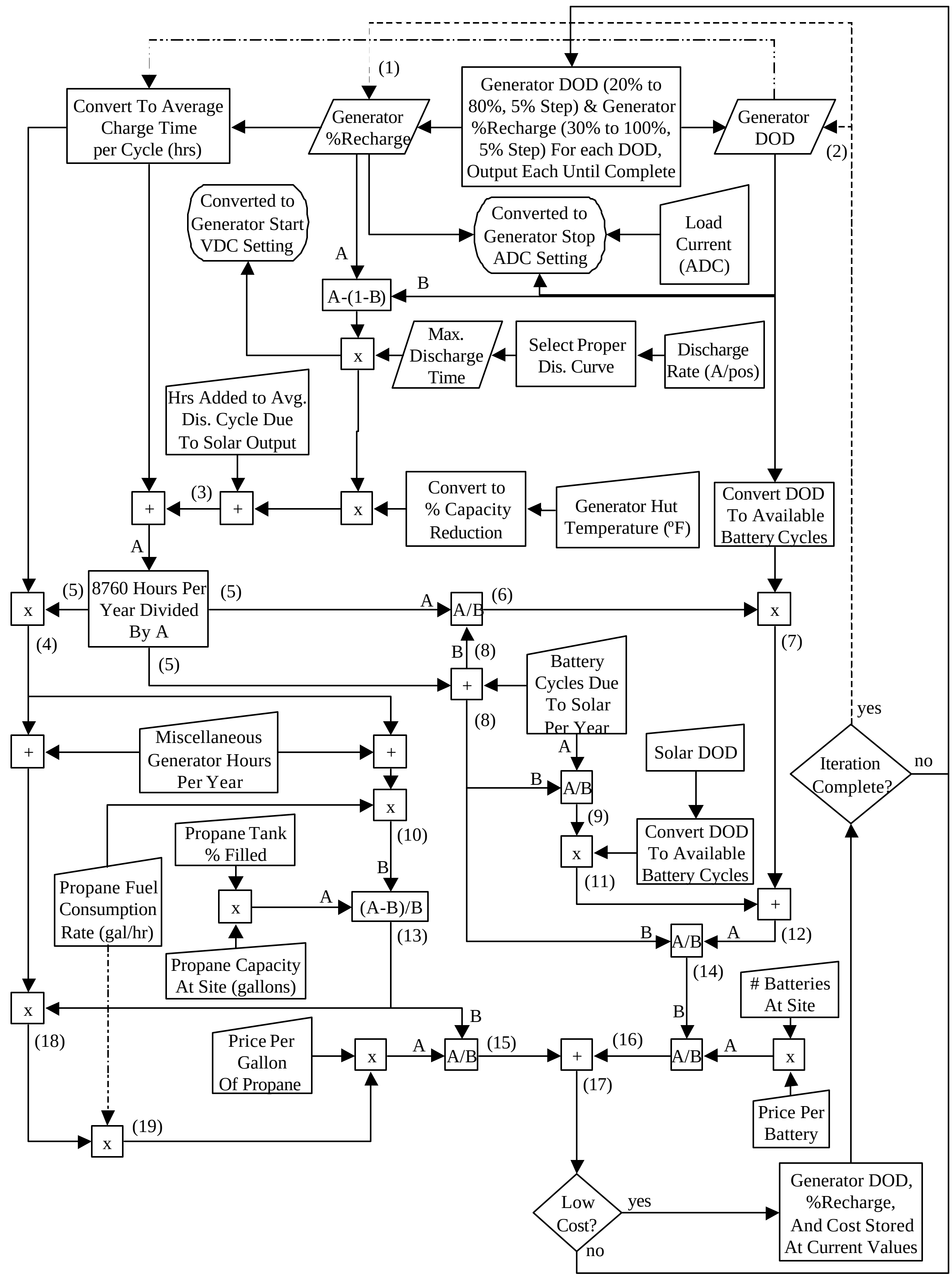

Figure 4-8. Optimization Flowchart.

Initially, the DOD used to calculate the VDC setting that starts the generator (labeled Generator DOD in the flowchart) during the charging process is set at 20%. Next, the desired SOC (labeled Generator %Recharge in the flowchart) used to calculate the finish current setting that secures the generator is set at 85%. These two settings are automatically inputted when the spreadsheet is executed. The Generator DOD is iterated from 20% to 70% at a 5% increment. The Generator %Recharge is iterated for each Generator DOD from 100% less the Generator DOD to 100% at a 5% increment. Once this iteration is complete, the Generator DOD is set at 75% and the Generator %Recharge is set at 30%. At this point, the Generator %Recharge is iterated from 30% to 100% for both 75% and 80% Generator DOD. These two processes ensure that the Generator %Recharge is always greater than the battery's SOC after discharge (100% less the Generator DOD).

During each Generator %Recharge iteration, one decision point is always reached. At this decision point, if the currently calculated cost is lower than the cost in memory, the Generator DOD and %Recharge used to produce this low cost along with the low cost value replace each of their corresponding values previously in stored memory. After these new values are stored a second decision point is reached. At this decision point, if all iterations have taken place, the stored Generator DOD and %Recharge values are automatically placed into the proper cells in the spreadsheet to generate various values that occur at the lowest cost. At this point the optimization is complete. If either the currently calculated cost is not lower than the cost in memory or all iterations have not taken place, the iterative process continues.

Table (4-3) defines variables that are used in the equations developed to minimize cost at Duke Island and Robert Barron.

Quantity	Variable
Generator %Recharge	R_G
Generator DOD	DOD_G
Base Discharge Time (hrs.)	t_{Base}
Generator Hut Temperature Compensation Factor	T_f
Time Added to each Discharge Process Due to Solar Charge (hrs.)	t_S
Average Battery Charge Time per Cycle (hrs.)	t_c
Average Battery Discharge Time per Cycle (hrs.)	t_d
Battery Cycles per Year from Generator	$C_G(yr)$
Generator Run-Time per Year (hrs.)	$t_G(yr)$
Battery Cycles per Year from Solar	$C_S(yr)$
Total Battery Cycles per Year	C_T
Percent Battery Cycles per Year from Generator	$\%C_G(yr)$
Lifetime Available Battery Cycles at DOD_G	$C_L(G)$
Actual Available Battery Cycles at DOD_G	$C_A(G)$
Percent Battery Cycles per Year from Solar	$\%C_S(yr)$
Lifetime Available Battery Cycles at Solar DOD	$C_L(S)$
Actual Available Battery Cycles at Solar DOD	$C_A(S)$
Total Available Battery Cycles	C_A
Time Before Batteries are Unable to Support Load (yrs.)	$t_A(B)$
Miscellaneous Generator Run-Time per Year (hrs.)	$t_m(yr)$
Propane Fuel Consumption Rate (gal/hr)	P_r
Propane Fuel Consumed per Year (gals.)	$P_F(yr)$
Percent Propane Tanks Filled	$\%P_F$
Propane Capacity at Site (gals.)	P_C
Time Before Propane Tanks are Refueled (yrs.)	$t_A(P)$
Total Generator Run-Time (hrs.)	t_G
Total Propane Fuel Consumed (gals.)	P_F
Number of Batteries at Site	B_S

Table 4-3. Optimization Variables.

Table (4-4) defines the cost variables used to optimize the expenses at each site.

Cost Factor	Variable
Price per Gallon of Propane Fuel	P_P
Annual Cost of Propane Fuel	F
Price per Battery	P_B
Annual Cost of Batteries	B
Annual Cost of Propane Fuel and Batteries	C_{FB}

Table 4-4. Cost Variables for Optimization.

In Figure (4-8), special points of interest are labeled. Points (1) and (2) represent the optimal values for the Generator %Recharge and DOD, respectively. Point (3) represents the average time between generator charging processes. The equation used to calculate the value at Point (3), also referred to as the Average Battery Discharge Time per Cycle is shown in Equation (4.1).

$$t_d = t_{Base} T_f \left[R_G - (1 - DOD_G) \right] + t_s \tag{4.1}$$

Point (4) represents the total generator run-time for all charging processes in one year (Generator Run-Time per Year). The equation used to calculate the value at Point (4) is shown in Equation (4.2).

$$t_G(yr) = t_c C_G(yr) \tag{4.2}$$

Point (5) represents the number of battery cycles due to generator processes in one year (Battery Cycles per Year from Generator). The value at Point (5) is calculated from Equation (4.3).

$$C_G(yr) = \frac{8760 hr/yr}{t_c + t_d} \tag{4.3}$$

Point (6) represents the percentage of battery cycles due to generator processes for one year (Percent Battery Cycles per Year from Generator). Point (6) is calculated from Equation (4.4).

$$\%C_G(yr) = \frac{C_G(yr)}{C_T} \tag{4.4}$$

Point (7) represents the actual available battery cycles from generator processes (Actual Available Battery Cycles at DOD_G). The value at Point (7) is calculated from Equation (4.5).

$$C_A(G) = \%C_G(yr)C_L(G) \tag{4.5}$$

Point (8) represents the total number of battery cycles due to solar and generator processes in one year (Total Battery Cycles per Year). The value at Point (8) is calculated from Equation (4.6).

$$C_T = C_G(yr) + C_S(yr) \tag{4.6}$$

Point (9) represents the percentage of battery cycles due to solar processes for one year (Percent Battery Cycles per Year from Solar). The value at Point (9) is calculated from Equation (4.7).

$$\%C_S(yr) = \frac{C_S(yr)}{C_T} \tag{4.7}$$

Point (10) represents the number of gallons of propane consumed in one year at either site (Propane Fuel Consumed per Year). The value at Point (10) is calculated from Equation (4.8).

$$P_F(yr) = P_r[t_G(yr) + t_m(yr)] \tag{4.8}$$

Point (11) represents the actual available battery cycles from solar processes (Actual Available Battery Cycles at Solar DOD). The value at Point (11) is calculated from Equation (4.9).

$$C_A(S) = \%C_S(yr)C_L(S) \tag{4.9}$$

Point (12) represents the total available battery cycles from a combination of generator and solar processes (Total Available Battery Cycles). The value at Point (12) is calculated from Equation (4.10).

$$C_A = C_A(G) + C_A(S) \tag{4.10}$$

Point (13) represents the number of years a site can operate before it is normally refueled (Time Before Propane Tanks are Refueled). The value at Point (13) is calculate from Equation (4.11).

$$t_A(P) = \frac{\%P_F P_C - P_F(yr)}{P_F(yr)} \tag{4.11}$$

Point (14) represents the maximum number of years a bank of batteries can operate before it cannot support a load (Time Before Batteries are Unable to Support Load). The value at Point (14) is calculated from Equation (4.12).

$$t_A(B) = \frac{C_A}{C_T} \tag{4.12}$$

Point (15) represents the average cost per year at a site due to propane fuel consumption (Annual Cost of Propane Fuel). The value at Point (15) is calculated from Equation (4.13).

$$F = \frac{P_F P_P}{t_A(P)} \tag{4.13}$$

Point (16) represents the average cost per year due to battery consumption (Annual Cost of Batteries). The value at Point (16) is calculated from Equation (4.14).

$$B = \frac{B_S P_B}{t_A(B)} \tag{4.14}$$

Point (17) represents the average total cost per year due to propane fuel and battery consumption (Annual Cost of Propane Fuel and Batteries). The value at Point (17) is calculated from Equation (4.15).

$$C_{FB} = F + B \tag{4.15}$$

Point (18) represents the total hours the generator can run before it is normally refueled (Total Generator Run-Time). The value at Point (18) is calculated from Equation (4.16).

$$t_G = t_A(P)[t_G(yr) + t_m(yr)] \tag{4.16}$$

Point (19) represents the total gallons of propane consumed at a site before it is normally refueled (Total Propane Fuel Consumed). The value at Point (19) is calculated from Equation (4.17).

$$P_F = t_G P_r \tag{4.17}$$

3. Simulation Spreadsheet

The cost of propane fuel per gallon is used in the optimization spreadsheet. At Duke Island, the delivery cost of propane consists of labor, helicopter, and barge expenses while at Robert Barron the expenses only include labor and helicopter costs. The purchase price of propane is assumed to be $2/gallon. Table (4-5) breaks down the labor costs to refuel each site. [29]

Labor Expenses	**Duke Island**	**Robert Barron**
Labor Rate (working)	$85/hr	$85/hr
Labor Rate (helicopter)	$1,400/hr	$1400/hr
Labor Hours (working)	10	8
Labor Hours (helicopter)	2	1
Labor Cost (working)	$850	$680
Labor Cost (helicopter)	$2800	$1400
Total Labor Cost	$3650	$2080

Table 4-5. Propane Cost of Labor After [29].

The costs of flying the propane to Duke Island and Robert Barron along with using a barge at Duke Island are shown in Table (4-6).

Expenses	Duke Island	Robert Barron
Helicopter Rate	$850/hr	$1400/hr
Helicopter Hours	6.25	4.67
Barge Rate	$4000/day	N/A
Barge Days	1.67	N/A
Total Helicopter Cost	$5312.50	$6538
Total Barge Cost	$6680	N/A

Table 4-6. Propane Cost of Barge and Helicopter After [29].

Table (4-7) summarizes the labor, barge, and helicopter costs and computes a total cost per propane gallon.

	Duke Island	Robert Barron
Base Rate of Propane	$2/gal	$2/gal
Gallons to Refuel	1500	2000
Labor Cost	$3650	$2080
Labor Cost per Gal.	$2.43/gal	$1.04/gal
Helicopter Cost	$5312.50	$6538
Helicopter Cost per Gal.	$3.54/gal	$3.27/gal
Barge Cost	$6680	N/A
Barge Cost per Gal.	$4.45/gal	N/A
Total Cost per Gal.	$12.42/gal	$6.31/gal

Table 4-7. Propane Cost per Gallon After [29].

The cost per battery is used in the optimization spreadsheet. At Duke Island and Robert Barron, the delivery cost of batteries consists of labor, helicopter, and disposal expenses. The purchase price of one battery plus shipping to an airport near each site is $1008.29 (calculated based on the purchase and shipping of eight batteries). Table (4-8) breaks down the labor costs to refuel each site. [29]

Labor Expenses	Duke Island	Robert Barron
Labor Rate (working)	$214/hr	$214/hr
Labor Rate (helicopter)	$1,400/hr	$1400/hr
Labor Hours (working)	8	8
Labor Hours (helicopter)	2	1
Labor Cost (working)	$1712	$1712
Labor Cost (helicopter)	$2800	$1400
Total Labor Cost	$4512	$3112

Table 4-8. Battery Cost of Labor After [29].

The costs of flying the batteries to Duke Island and Robert Barron along with flying and disposing of the old batteries is shown in Table (4-9).

Expenses	Duke Island	Robert Barron
Helicopter Rate	$1400/hr	$1400/hr
Helicopter Hours	5	2.67
Disposal Labor Cost	$214	$214
Disposal Fee	$175	$175
Total Helicopter Cost	$7000	$3738
Total Disposal Cost	$389	$389

Table 4-9. Battery Cost of Helicopter and Disposal After [29].

Table (4-10) combines all the costs and computes a total cost per battery.

	Duke Island	**Robert Barron**
Base Cost of Batteries	$1008.29/battery	$1008.29/battery
Batteries to Replace	8	8
Labor Cost	$4512	$3112
Labor Cost per Bat.	$564/battery	$389/battery
Helicopter Cost	$7000	$3738
Helicopter Cost per Bat.	$875/battery	$467.25/battery
Disposal Cost	$389	$389
Disposal Cost per Bat.	$48.63/battery	$48.63/battery
Total Cost per Bat.	$2495.92	$1913.17

Table 4-10. Cost per Battery After [29].

The simulation spreadsheet operates as the simulation flowchart indicates. Figure (4-9) displays the user input section of the spreadsheet.

Propane Generator Required Inputs					
Price per Gallon of Propane (Including Delivery Costs)	Site Propane Capacity (gal)	% Propane Tanks Filled	Average Generator Hut Temperature (°F)	Rate of Propane Consumption (gal/hr)	Miscellaneous Generator Run-Time per Year (hrs.)
		80%	32 35 38 41	1.00	

Battery Required Inputs			Solar Required Inputs		
Price per Battery (Including Delivery Costs)	Number of Batteries at Site	Load Current (Amps)	Solar Charge Time Added per Discharge Process (hrs.)	Average Battery DOD Prior to Solar Charge	Number of Battery Cycles per Year Due to Solar Charging
	8			20% 25% 30% 35%	

Figure 4-9. Spreadsheet Input Section.

The inputs vary depending on whether Duke Island or Robert Barron is selected. The inputs are determined by a combination of historical data and current equipment power requirements. The fuel consumption rate of 1.0 gal/hr is based roughly on a 71% load. This value may be parameterized provided timely data from the vendor.

Figure (4-10) illustrates the various values computed by the spreadsheet including the cost per year and generator settings. The optimized cost is displayed when the "Optimize Annual Cost (Click)" button is activated. The code created to optimize the cost is listed in Appendix A. The total cost changes if any inputs or if the Generator DOD or %Recharge changes.

Propane Generator Spreadsheet Calculated Outputs

Generator Charging Cycles per Year (Battery Cycles Due to Generator)	Average Charging Generator Run-Time per Cycle (hrs.)	Charging Generator Run-Time per Year (hrs.)	Total Generator Run-Time per Year (hrs.)	Average Propane Fuel Consumed per Year (gal)	Propane Fuel Available for Generator at Site (gal)
#N/A	#N/A	#N/A	#N/A	#N/A	0

Years Before Propane Tanks Refueled at Site	Total Generator Charging Cycles Prior to Refueling	Total Miscellaneous Generator Run-Time Prior to Refueling (hrs.)	Total Charging Generator Run-Time Prior to Refueling (hrs.)	Total Generator Run-Time Prior to Refueling (hrs.)	Total Amount of Propane Consumed Prior to Refueling (gal)
#N/A	#N/A	#N/A	#N/A	#N/A	#N/A

VRLA Battery Spreadsheet Calculated Outputs

Battery DOD Prior to Generator Start	Battery %Recharge Prior to Generator Stop	Average Time Between Generator Starts (Discharge Time)	Number of Battery Cycles per Year Including Solar and Generator Processes
		0.00	#N/A

Percent Battery Cycles per Year Due to Generator Charging	Percent Battery Cycles per Year Due to Solar Charging	Discharge Rate (A/pos)	Battery Lifetime Available Cycles Including Solar and Generator Processes	Years Until Batteries are Useless
#N/A	#N/A	0.00	#N/A	#N/A

Spreadsheet Calculated Costs and Generator Settings

Annual Cost of Propane	Annual Cost of Batteries	Total Annual Cost	Optimize Annual Cost (Click)	Generator Start Voltage Setting	Generator Finish Current Setting
#N/A	#N/A	#N/A	$0.00		

Figure 4-10. Spreadsheet Calculated Outputs Section.

Both the Generator Start Voltage Setting and Generator Finish Current Setting are not automatically calculated by the spreadsheet. At this time it is recommended that the user perform the calculations for these two settings as described in Chapter II. However, it is important that appropriate extrapolation be done to ensure that the settings reflect the true battery DOD and percent recharge values that the user deems optimal.

In order to obtain various data for the spreadsheet, it was necessary to convert the applicable characteristic battery curves from Chapters II and III into data tables. Figure (4-11) illustrates the data tables used to compensate for temperature and convert DOD to lifetime available cycles.

Temperature Compensation	
Temperature (°F)	Factor
32	0.71
35	0.726
38	0.743
41	0.76
44	0.786
47	0.813
50	0.84
53	0.86
56	0.88
59	0.9
62	0.916
65	0.933
68	0.95
71	0.966
74	0.983
77	1

Available Battery Cycles	
DOD	Cycles
20%	5000
25%	4475
30%	4000
35%	3550
40%	3150
45%	2800
50%	2500
55%	2240
60%	2000
65%	1780
70%	1580
75%	1390
80%	1200

Figure 4-11. Temperature Compensation and Available Battery Cycles Tables.

Figure (4-12) displays the data table used to determine the number of hours for a generator charging process based on the Generator DOD and %Recharge. All values with the exception of the 80% DOD column were extrapolated from actual data in Figure (2-3) and are based on lead-acid battery theory. In the future, it is recommended that actual measurements be taken at the various DODs listed in Figure (4-12).

Charging Generator Run-Time per Cycle (Hours)													
Percent Recharge / DOD	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%
30%											0.25	0.3	1.3
35%										0.25	0.3	0.9	1.5
40%									0.25	0.35	0.6	1.2	1.75
45%								0.25	0.4	0.7	1	1.5	2
50%							0.25	0.45	0.75	1.1	1.4	1.85	2.25
55%						0.25	0.5	0.9	1.25	1.5	1.75	2.15	2.5
60%					0.25	0.6	1.1	1.45	1.75	2.1	2.4	2.65	2.9
65%				0.25	1	1.4	1.75	2.1	2.4	2.65	2.9	3.15	3.4
70%			0.25	1.2	2	2.4	2.75	3	3.25	3.45	3.6	3.75	3.9
75%		0.25	1.25	2.5	3.2	3.45	3.7	3.95	4.2	4.35	4.5	4.55	4.6
80%	0.25	1.75	3	4.25	4.7	4.85	5	5.15	5.3	5.45	5.6	5.6	5.6
85%	1.85	3.9	5.25	6.25	6.5	7	7	7	7	7	7	7	7
90%	6	7.5	8.5	9	9	9	9	9	9	9	9	9	9
95%	12	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3
100%	30	30	30	30	30	30	30	30	30	30	30	30	30

Figure 4-12. Charging Generator Run-Time per Cycle Table.

4. Solar Impact

The variability of power provided by the solar arrays creates inaccuracies with the results of the simulation. Since the total time that the solar arrays provide power per year is averaged down to a number of hours per cycle, the simulation treats solar power as if it is a consistent and reliable source of energy. However, as empirical data from the sites indicate, solar power varies daily. The simulation assumes a constant contribution to the time of the discharge process (time between generator starts) to reflect the solar contribution per cycle. As a result, a much smaller requirement of power is needed from the generator during times when solar power is scarce and a greater requirement of power is needed from the generator when solar power is abundant than what the simulation indicates. To clarify, during extremely sunny months the actual time between generator starts (discharge time) is greater than the average discharge time calculated by the spreadsheet. In this case, the simulated generator run-time is higher than it needs to be to satisfy the power requirement. In the case when there is very little sun, the same simulated generator run-time is not enough to meet the power demand at the site.

To more accurately set the generator start and stop thresholds, it is recommended that more research be conducted. It is possible that the optimal Generator DOD and

%Recharge can be determined assuming that there is no solar power contribution. Since the average solar process DOD corresponds to a much higher number of available lifetime battery cycles than the Generator DOD, the effect of solar power on battery lifetime may be insignificant. The optimal Generator DOD and %Recharge can then be manually entered into the spreadsheet with the estimated solar power contribution to determine various outputs.

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V. ALTERNATIVE STRATEGIES

A. HYBRID ALTERNATIVE CONFIGURATION

1. General

Excluding the installation costs of the new system, annual propane fuel and battery cost reductions can be achieved through the implementation of an alternative configuration for supplying power to the electrical loads and charging the battery strings. The alternative configuration increases battery life and decreases generator run-time. [30]

2. Basic Operation

Figure (5-1) illustrates a typical charging process for a lead-acid battery. It is similar to the charging characteristics of the batteries discussed in this thesis. A constant-current interval is followed by a constant-voltage interval in which the charge current tapers off. The finish charging final value represents a compromise between generator run-time and battery percent recharge.

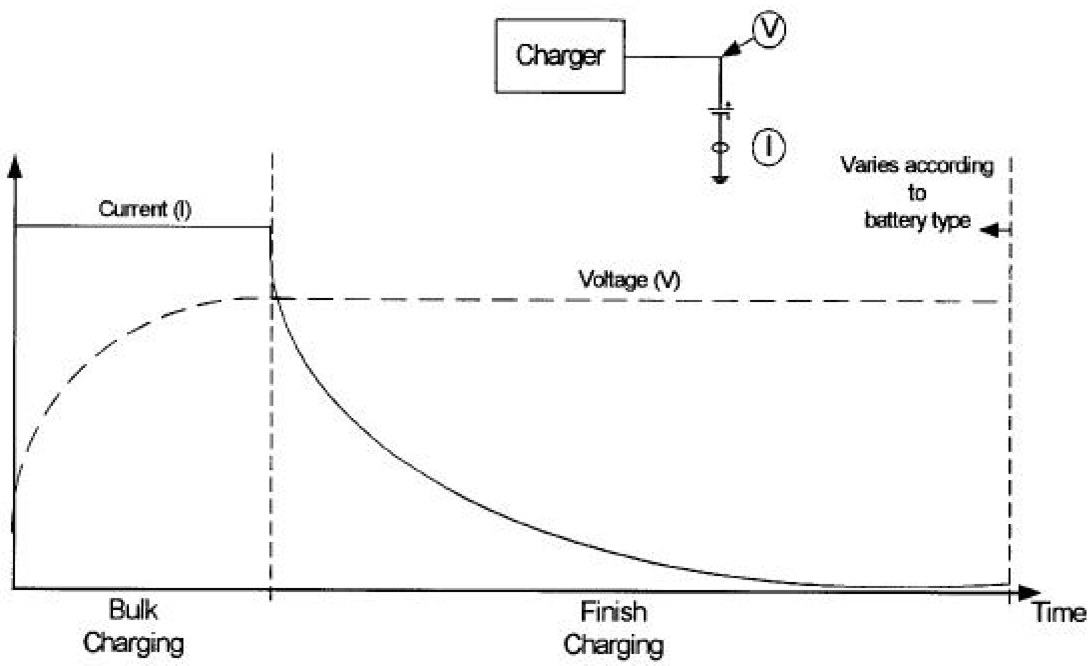

Figure 5-1. Lead-Acid Battery Charging Profile From [30].

With the alternative configuration, the generator charges each battery string during the bulk charging period. Once the bulk charging is complete, the generator stops and finish charging is carried out on one battery string by the other battery string. The battery string that supplies the finish current powers the load as well. At the NDS sites (standard configuration), the generator provides bulk and finish charging to both battery strings simultaneously. [30]

Since the bulk charging period is generally much shorter than the finish charging period, the generator will operate for shorter durations when the alternative configuration is used. However, if the battery capacity of the alternative configuration remains identical to that of the standard configuration, the generator must run more often to deliver the same amount of power because of the increase in discharge rate during finish charging. The total generator run-time of the alternative configuration should be less than the standard configuration because the generator runs more efficiently with the alternative configuration. The amount of power delivered during bulk charging is much closer to the rated load than during finish charging. Generators are more efficient when operated near their rated load. Therefore, the generator delivers the same amount of power as with a standard configuration but it does so more efficiently. Since it runs more efficiently, the generator does not need to run as long as it would during less efficient modes of operation (small loads).

Figure (5-2) is a schematic of the alternative configuration. In this schematic, the load requires AC while at the NDS sites DC is required to power the load. The schematic with the exception of the AC to DC and DC to AC converters shows how the NDS sites would operate with the alternative configuration.

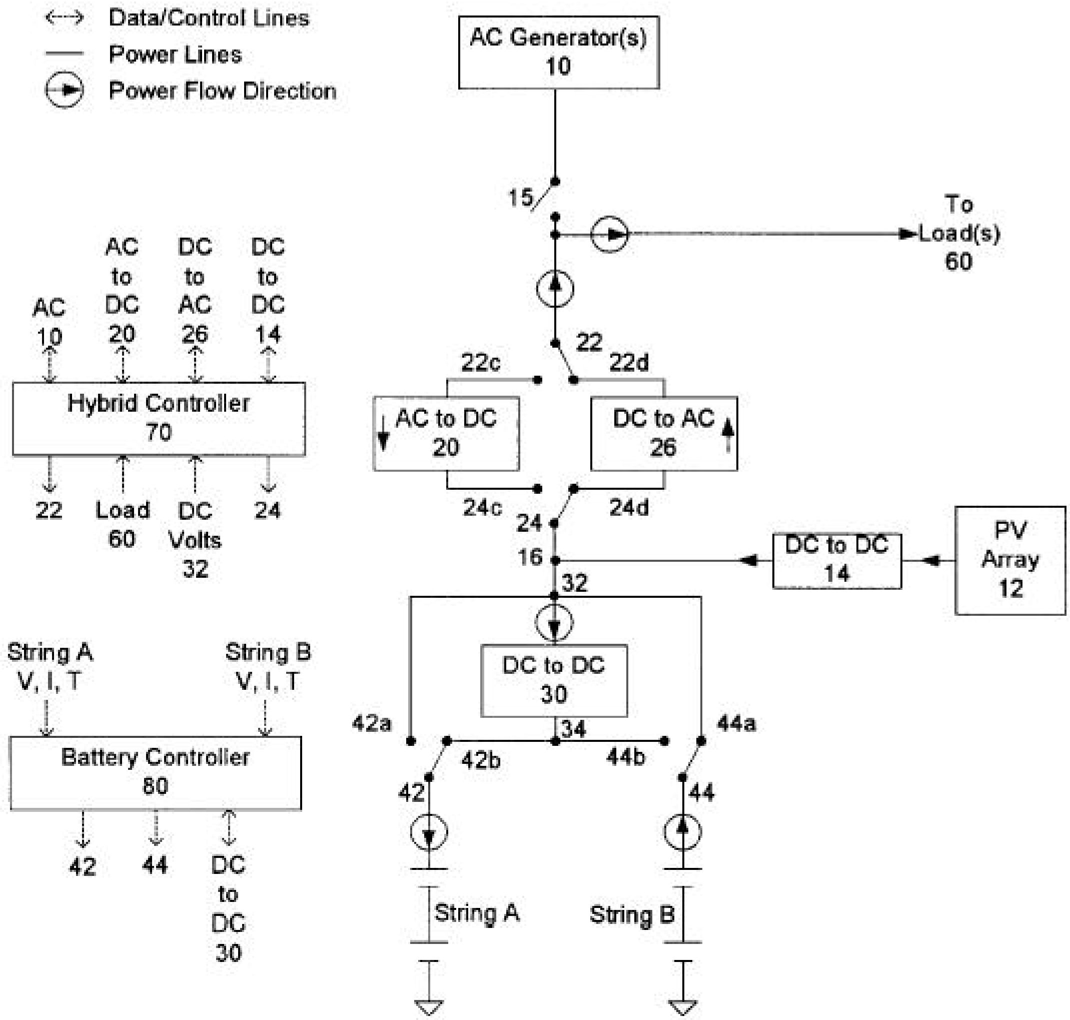

Figure 5-2. Alternative Configuration From [30].

As depicted in Figure (5-2), Battery String B is currently supplying power to the load while finish charging Battery String A via a boost dc-dc converter. During normal discharging, switches (42) and (44) are in position (42a) and (44a), respectively. In this position, the two battery strings are discharged to a preset DOD at which time the generator starts and bulk charging commences. When bulk charging ceases, switch (44) is moved to the (44b) position. At this point, String A is finish charging String B while providing enough power to supply the load. String A continues to charge String B until it is fully charged. Once String B is fully charged, switch (44) moves to the (44a) position and both strings are discharged to supply the load. The next time the battery strings are charged, String B finish charges String A as shown in Figure (5-2). The process continues with each string being finish charged every other cycle. [30]

During the process described in the previous paragraph, Battery Controller 80 (shown in Figure (5-2)) monitors the voltage, current, and temperature of each battery string. These values allow the controller to properly determine when to connect and disconnect the battery strings to the dc-dc converter. In particular, the current sensor allows for Amp-Hour counting (discussed in detail in Section B), which ensures accurate battery management. The dc-dc converter increases the voltage output from one battery string to a level that allows the other battery string to finish charge safely and efficiently. Hybrid Controller 70 is functionally similar to the control system at the NDS sites. [30]

The voltage and current of String A and String B vary during the charging and discharging processes as illustrated in Figure (5-3). The plot in Figure (5-3) is the result of prototype testing executed by the inventors of the alternative configuration. The prototype consisted of two battery strings, a generator, and load. The design used in the prototype was not intended to bear resemblance to any NDS hybrid power system. [30]

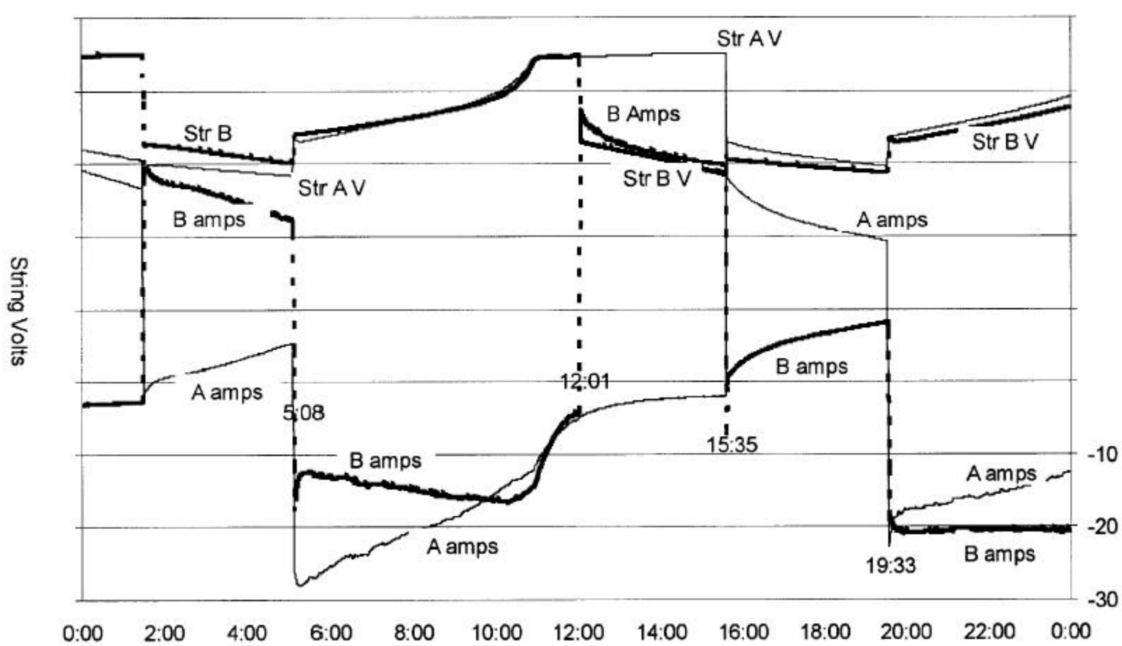

Figure 5-3. Alternative Configuration Voltage and Current Profiles From [30].

In Figure (5-3) the voltage and current for String A and String B are plotted over a 24-hour period. Immediately prior to 2:00, String A and String B are configured in the discharge mode. Both strings are discharged until 5:08. During this discharge period the string currents (A amps and B amps) appear to be converging. At 5:08, bulk charging begins and continues until 12:01. At 12:01, the bulk charge is complete and String B finish charges String A and maintains the load. During the finish charge period, String A's voltage (Str A V) is slightly higher than it was at the end of the bulk charge. Meanwhile, String B's voltage (Str B V) is exponentially decreasing. Also during this finish charging period, String B's current is much higher than String A's current as a result of supporting the load and providing a finish charge for String A. At 15:35, the finish charge is complete, commencing the discharging process causing String B's current to instantly plummet below String A's current because String A's voltage is higher than String B's voltage. At 19:33, the discharging process ends and the bulk charging begins. When the bulk charge is complete this time, String A will finish charge String B. [30]

3. Advantages and Drawbacks

As previously mentioned, the alternative configuration provides a fuel savings over the standard configuration. The fuel savings stems from operating the generator at a higher fuel efficiency thereby decreasing the generator run-time needed to recharge the batteries to the same SOC used in the standard configuration. Additionally, the alternative configuration increases battery lifetime.

The increase in battery lifetime is due to the higher level of percent recharge that each battery receives over a battery in the standard configuration. In the alternative configuration, every other cycle one string of batteries is fully recharged. In the standard configuration, a 90% recharge is normally higher than most applications regularly use. Assuming two battery strings and a 90% bulk recharge, the alternative configuration would essentially deplete the fuel required for a 90% recharge but provide an overall percent recharge of 95% as compared with the standard configuration. The higher the percent recharge, the more time in between cycles. Since a battery's lifetime is measured in cycles, the fewer cycles used, the longer the lifetime of the battery.

Another advantage of the alternative configuration again stems from the 100% recharge. Nearly all lead-acid batteries require an equalization charge or they suffer lifetime and capacity degradation. By charging a battery back to its original capacity, the need to equalize is eliminated [30]. In the standard configuration, the generator is typically used to equalize battery cells. Without an equalization charge, a cost savings through reduced fuel consumption is realized.

The major disadvantage of implementing the alternative configuration at the NDS sites is initial costs. The battery capacity needs to be reconfigured to ensure that the generator runs optimally and the load can be supported by one battery string. If two battery strings are required to support the load, a third string would probably need to be installed. In this three-string scenario, the alternative configuration operates similarly with each string being finish charged by the other two strings every third cycle. The installation of additional batteries is costly. However, once the initial costs are incurred, the alternative configuration provides a cost savings when compared to the standard configuration.

B. AMPERE-HOUR COUNTING

It is nearly impossible to use the alternative configuration with the same type of control system that the NDS sites employ. The alternative configuration keeps track of the number of ampere-hours that are discharged by the load and charged into the batteries.

In order to determine the number of ampere-hours discharged by the load, a current shunt monitors each battery string. The number of amps passing through the shunt is continually summed by equipment connected to the current shunt. During the charging process, more than 100% of the ampere-hours that were discharged from the batteries are given back to account for inefficiencies during the charging process.

Ampere-hour counting allows generator settings to be entered as percentages as opposed to voltages and currents. Therefore, if the capacity of a battery in ampere-hours is known prior to its first discharge, then that battery's SOC can be found by subtracting the number of ampere-hours measured by the current shunt from the capacity, and then dividing the result by the capacity.

Through the use of ampere-hour counting, the chances of over-discharging are reduced because of its improved accuracy beyond standard procedures in determining a battery's DOD. Additionally, it is safer to completely recharge a battery when ampere-hour counting than when using typical methods to determine SOC because with ampere-hour counting the actual finish current does not need to be known, only the number of ampere-hours discharged plus those needed to overcome inefficiencies are necessary.

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VI. OPERATING SCENARIO STUDY

A. DEFINITION

The estimated current costs associated with running Duke Island and Robert Barron along with optimized costs provided by the spreadsheet are discussed in this chapter. Three different costs are shown for each site when optimized. One cost assumes no solar contribution while another allows the spreadsheet to optimize with solar contributions averaged per cycle. The third cost uses the Generator DOD and %Recharge settings found in the simulation without the solar contribution and fixes these values in the simulation with solar contributions averaged per cycle. Fuel consumption is assumed to be 1 gal/hr. The time to discharge is extrapolated based on past and future loads as applicable.

The costs discussed in the preceding paragraph are compared to the costs computed when using the alternative configuration. The costs shown when using the alternative configuration are lower than they would actually be. The costs should be higher due to a higher discharge rate throughout the finish charging period resulting in a more frequent charging interval. Essentially, the alternative configuration optimization simulation only shows the effect that an increase in percent recharge would have without increasing the amount of fuel consumed, which would likely occur due to a more frequent charging interval. To maintain the same charging interval that is presently observed at each site, more battery strings and/or higher capacity batteries would need to be installed at each site using the alternative configuration. The costs shown for the alternative configuration do not include the costs of installing more battery strings and/or higher capacity batteries.

In Section B, spreadsheet-calculated results for inputs that are almost identical to actual conditions at Duke Island during 2001 are provided. These results can be compared to actual data to assess the spreadsheet's accuracy. In section C, the performance and annual costs of each site based on current generator settings and the loads presented in Chapter II are projected. In Section D, the spreadsheet calculates optimal generator settings assuming there is no solar contribution. These two generator settings are subsequently hard-wired into the spreadsheet to predict site performance with the same solar contribution measured during 2001. Additionally, in Section D, the spreadsheet optimizes the generator settings based on 2001 solar data and predicts the future performance of each site using these optimal generator settings and the loads presented in Chapter II. In Section E, the spreadsheet optimizes the generator settings based on the alternative configuration and solar data from 2001 to predict the future performance of each site using these optimal values and the loads presented in Chapter II. In Section F, a brief summary of the results is provided.

B. ESTIMATED COSTS BASED ON PAST DATA AT DUKE ISLAND

Figure (6-1) shows the required input section after the appropriate data is entered. The inputs include a 12 A load, which was estimated for the year 2001. Additionally, the Generator DOD and %Recharge are fixed at 60% and 85%, respectively. These values are also estimated based on data from 2001.

Propane Generator Required Inputs					
Price per Gallon of Propane (Including Delivery Costs)	Site Propane Capacity (gal)	% Propane Tanks Filled	Average Generator Hut Temperature (°F)	Rate of Propane Consumption (gal/hr)	Miscellaneous Generator Run-Time per Year (hrs.)
$12.42	2,500	80%	59 62 65 68	1.00	0.80

Battery Required Inputs			Solar Required Inputs		
Price per Battery (Including Delivery Costs)	Number of Batteries at Site	Load Current (Amps)	Solar Charge Time Added per Discharge Process (hrs.)	Average Battery DOD Prior to Solar Charge	Number of Battery Cycles per Year Due to Solar Charging
$2,495.92	8	12.00	24.97	20% 25% 30% 35%	262.00

Figure 6-1. Past Settings at Duke Island.

The results from for this site, based on the inputs in Figure (6-1), are shown in Figure (6-2). The data shown in Figure (6-2) can be used to compare the predicted results from the spreadsheet with actual data collected during 2001. The Battery DOD Prior to Generator Start (60%), Battery %Recharge Prior to Generator Stop (85%), Years Before Propane Tanks Refueled at Site (2.82), Years Until Batteries are Useless (11.66), and the Total Annual Cost ($8,209.58) provide a brief overview useful for comparison with the other simulations presented in this chapter.

Propane Generator Spreadsheet Calculated Outputs					
Generator Charging Cycles per Year (Battery Cycles Due to Generator)	Average Charging Generator Run-Time per Cycle (hrs.)	Charging Generator Run-Time per Year (hrs.)	Total Generator Run-Time per Year (hrs.)	Average Propane Fuel Consumed per Year (gal)	Propane Fuel Available for Generator at Site (gal)
74.62	7	522.36	523.16	523.16	2,000
Years Before Propane Tanks Refueled at Site	Total Generator Charging Cycles Prior to Refueling	Total Miscellaneous Generator Run-Time Prior to Refueling (hrs.)	Total Charging Generator Run-Time Prior to Refueling (hrs.)	Total Generator Run-Time Prior to Refueling (hrs.)	Total Amount of Propane Consumed Prior to Refueling (gal)
2.82	210.65	2.26	1,474.58	1,476.84	1,476.84

VRLA Battery Spreadsheet Calculated Outputs				
Battery DOD Prior to Generator Start	Battery %Recharge Prior to Generator Stop	Average Time Between Generator Starts (Discharge Time)	Number of Battery Cycles per Year Including Solar and Generator Processes	
60%	85%	110.47	336.62	
Percent Battery Cycles per Year Due to Generator Charging	Percent Battery Cycles per Year Due to Solar Charging	Discharge Rate (A/pos)	Battery Lifetime Available Cycles Including Solar and Generator Processes	Years Until Batteries are Useless
22.17%	77.83%	0.75	3,926.34	11.66

Spreadsheet Calculated Costs and Generator Settings					
Annual Cost of Propane	Annual Cost of Batteries	Total Annual Cost	Optimize Annual Cost (Click)	Generator Start Voltage Setting	Generator Finish Current Setting
$6,497.69	$1,711.90	$8,209.58	N/A		

Figure 6-2. Duke Island Estimates of Past Parameters.

C. FUTURE PREDICTIONS FOR CURRENT GENERATOR SETTINGS

1. Duke Island

Figure (6-3) shows the inputs used to generate all future predictions in the remainder of this chapter for Duke Island. The numbers used in the input section are taken from Chapter II. The load current is 14.40 A as shown in Figure (6-3) vice 12.00 A in Figure (6-1).

Propane Generator Required Inputs

Price per Gallon of Propane (Including Delivery Costs)	Site Propane Capacity (gal)	% Propane Tanks Filled	Average Generator Hut Temperature (°F)	Rate of Propane Consumption (gal/hr)	Miscellaneous Generator Run-Time per Year (hrs.)
$12.42	2,500	80%	59 62 65 68	1.00	0.80

Battery Required Inputs			Solar Required Inputs		
Price per Battery (Including Delivery Costs)	Number of Batteries at Site	Load Current (Amps)	Solar Charge Time Added per Discharge Process (hrs.)	Average Battery DOD Prior to Solar Charge	Number of Battery Cycles per Year Due to Solar Charging
$2,495.92	8	14.40	24.97	20% 25% 30% 35%	262.00

Figure 6-3. Current Settings at Duke Island.

Figure (6-4) shows the predicted results if these inputs remain constant and the generator settings do not change. The Battery DOD Prior to Generator Start (60%), Battery %Recharge Prior to Generator Stop (85%), Years Before Propane Tanks Refueled at Site (2.61), Years Until Batteries are Useless (11.45), and the Total Annual Cost ($8,616.92) provide a brief overview useful for comparison with the other simulations presented in this chapter.

Propane Generator Spreadsheet Calculated Outputs					
Generator Charging Cycles per Year (Battery Cycles Due to Generator)	Average Charging Generator Run-Time per Cycle (hrs.)	Charging Generator Run-Time per Year (hrs.)	Total Generator Run-Time per Year (hrs.)	Average Propane Fuel Consumed per Year (gal)	Propane Fuel Available for Generator at Site (gal)
78.93	7	552.52	553.32	553.32	2,000
Years Before Propane Tanks Refueled at Site	Total Generator Charging Cycles Prior to Refueling	Total Miscellaneous Generator Run-Time Prior to Refueling (hrs.)	Total Charging Generator Run-Time Prior to Refueling (hrs.)	Total Generator Run-Time Prior to Refueling (hrs.)	Total Amount of Propane Consumed Prior to Refueling (gal)
2.61	206.37	2.09	1,444.58	1,446.68	1,446.68

VRLA Battery Spreadsheet Calculated Outputs				
Battery DOD Prior to Generator Start	Battery %Recharge Prior to Generator Stop	Average Time Between Generator Starts (Discharge Time)	Number of Battery Cycles per Year Including Solar and Generator Processes	
60%	85%	104.06	340.93	
Percent Battery Cycles per Year Due to Generator Charging	Percent Battery Cycles per Year Due to Solar Charging	Discharge Rate (A/pos)	Battery Lifetime Available Cycles Including Solar and Generator Processes	Years Until Batteries are Useless
23.15%	76.85%	0.90	3,901.99	11.45

Spreadsheet Calculated Costs and Generator Settings					
Annual Cost of Propane	Annual Cost of Batteries	Total Annual Cost	Optimize Annual Cost (Click)	Generator Start Voltage Setting	Generator Finish Current Setting
$6,872.29	$1,744.63	$8,616.92	N/A		

Figure 6-4. Duke Island Predictions for Current Settings.

2. Robert Barron

Figure (6-5) shows the input section for Robert Barron with inputs taken from Chapter II.

Propane Generator Required Inputs					
Price per Gallon of Propane (Including Delivery Costs)	Site Propane Capacity (gal)	% Propane Tanks Filled	Average Generator Hut Temperature (°F)	Rate of Propane Consumption (gal/hr)	Miscellaneous Generator Run-Time per Year (hrs.)
$6.31	3,500	80%	59 62 65 68	1.00	3.47

Battery Required Inputs			Solar Required Inputs		
Price per Battery (Including Delivery Costs)	Number of Batteries at Site	Load Current (Amps)	Solar Charge Time Added per Discharge Process (hrs.)	Average Battery DOD Prior to Solar Charge	Number of Battery Cycles per Year Due to Solar Charging
$1,913.17	8	19.00	7.24	20% 25% 30% 35%	81.00

Figure 6-5. Current Settings at Robert Barron.

These numbers remain constant throughout the remainder of this chapter. Figure (6-6) illustrates the predicted performance at Robert Barron based on the inputs in Figure (6-5) and constant Generator DOD and %Recharge settings. The Battery DOD Prior to Generator Start (60%), Battery %Recharge Prior to Generator Stop (85%), Years Before Propane Tanks Refueled at Site (1.88), Years Until Batteries are Useless (14.18), and the Total Annual Cost ($7,208.47) provide a brief overview useful for comparison with the other simulations presented in this chapter.

Propane Generator Spreadsheet Calculated Outputs

Generator Charging Cycles per Year (Battery Cycles Due to Generator)	Average Charging Generator Run-Time per Cycle (hrs.)	Charging Generator Run-Time per Year (hrs.)	Total Generator Run-Time per Year (hrs.)	Average Propane Fuel Consumed per Year (gal)	Propane Fuel Available for Generator at Site (gal)
138.26	7	967.82	971.29	971.29	2,800

Years Before Propane Tanks Refueled at Site	Total Generator Charging Cycles Prior to Refueling	Total Miscellaneous Generator Run-Time Prior to Refueling (hrs.)	Total Charging Generator Run-Time Prior to Refueling (hrs.)	Total Generator Run-Time Prior to Refueling (hrs.)	Total Amount of Propane Consumed Prior to Refueling (gal)
1.88	260.31	6.53	1,822.18	1,828.71	1,828.71

VRLA Battery Spreadsheet Calculated Outputs

Battery DOD Prior to Generator Start	Battery %Recharge Prior to Generator Stop	Average Time Between Generator Starts (Discharge Time)	Number of Battery Cycles per Year Including Solar and Generator Processes
60%	85%	56.40	219.26

Percent Battery Cycles per Year Due to Generator Charging	Percent Battery Cycles per Year Due to Solar Charging	Discharge Rate (A/pos)	Battery Lifetime Available Cycles Including Solar and Generator Processes	Years Until Batteries are Useless
63.06%	36.94%	1.19	3,108.28	14.18

Spreadsheet Calculated Costs and Generator Settings

Annual Cost of Propane	Annual Cost of Batteries	Total Annual Cost	Optimize Annual Cost (Click)	Generator Start Voltage Setting	Generator Finish Current Setting
$6,128.82	$1,079.65	$7,208.47	N/A		

Figure 6-6. Robert Barron Predictions for Current Settings.

D. OPTIMIZED PREDICTIONS

1. Predictions Made Assuming No Solar Contribution

In this section, optimal generator settings are calculated based on inputs not including any contribution from the photovoltaic arrays at each site. The purpose of this section is only to produce one pair of Generator DOD and %Recharge settings to enter into the spreadsheet to predict future performance based on these optimal values without the solar contribution. The generator and battery performances are not illustrated because they are not reasonable since there should always be a solar contribution. However, the manner in which the cost varies with generator settings (DOD and percent recharge) is depicted in a plot for each site.

a. Duke Island

After running the simulation, the optimal Generator DOD and %Recharge settings were found to be 80% and 70%, respectively. The graph in Figure (6-7) shows how the cost varies. The lowest costs calculated by the spreadsheet appear in the graph in the rectangular region delineated by 60% to 80% Generator DOD and 45% to 80% Generator %Recharge.

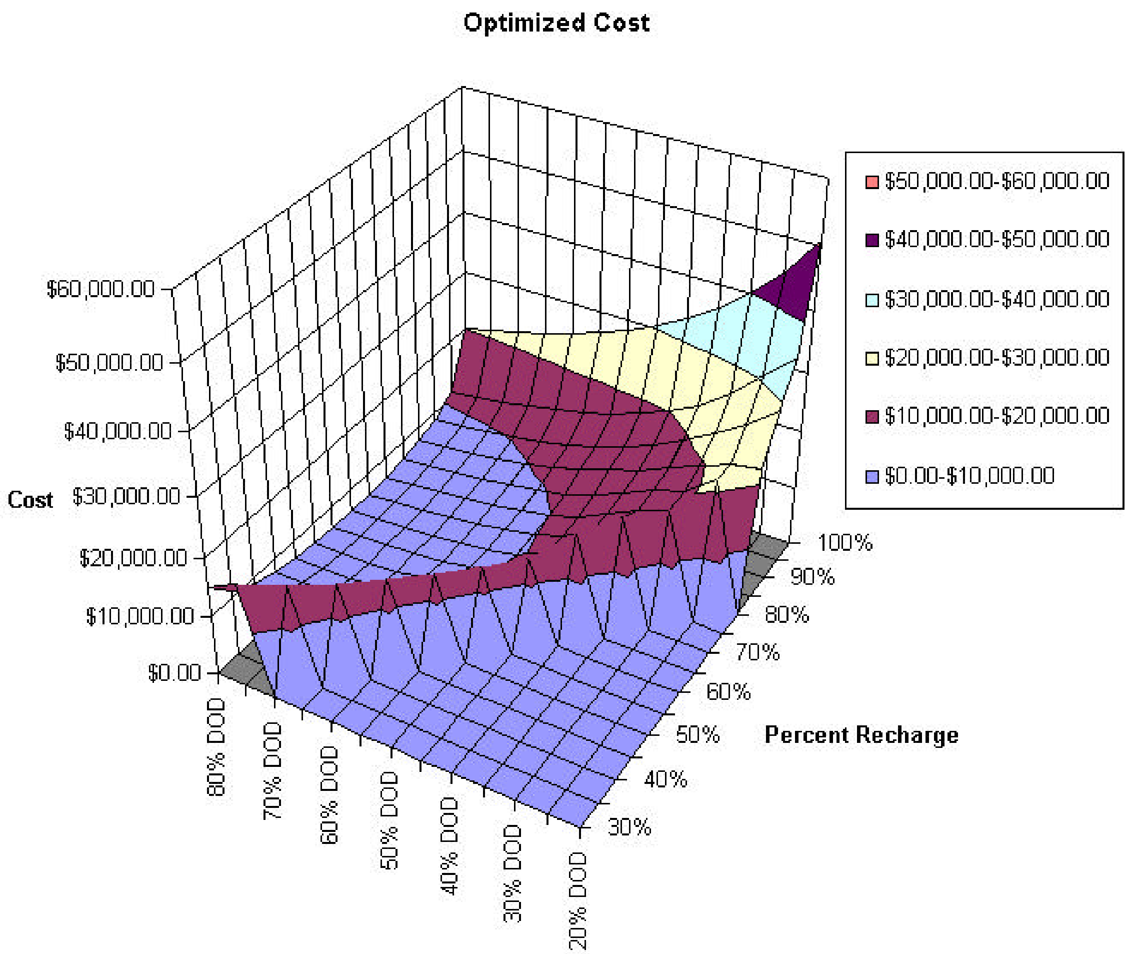

Figure 6-7. Cost Variation at Duke Island without the Solar Contribution.

b. Robert Barron

The optimal Generator DOD was determined to be 80%, while the optimal Generator %Recharge was found to be 70%, after running the spreadsheet simulation with no solar contribution. The graph in Figure (6-8) pictures the cost variation during the simulation. The lowest costs calculated by the spreadsheet appear in the graph in the rectangular region delineated by 55% to 80% Generator DOD and 40% to 90% Generator %Recharge. This region provides sub-optimal alternatives whose associated costs are close to the optimal cost.

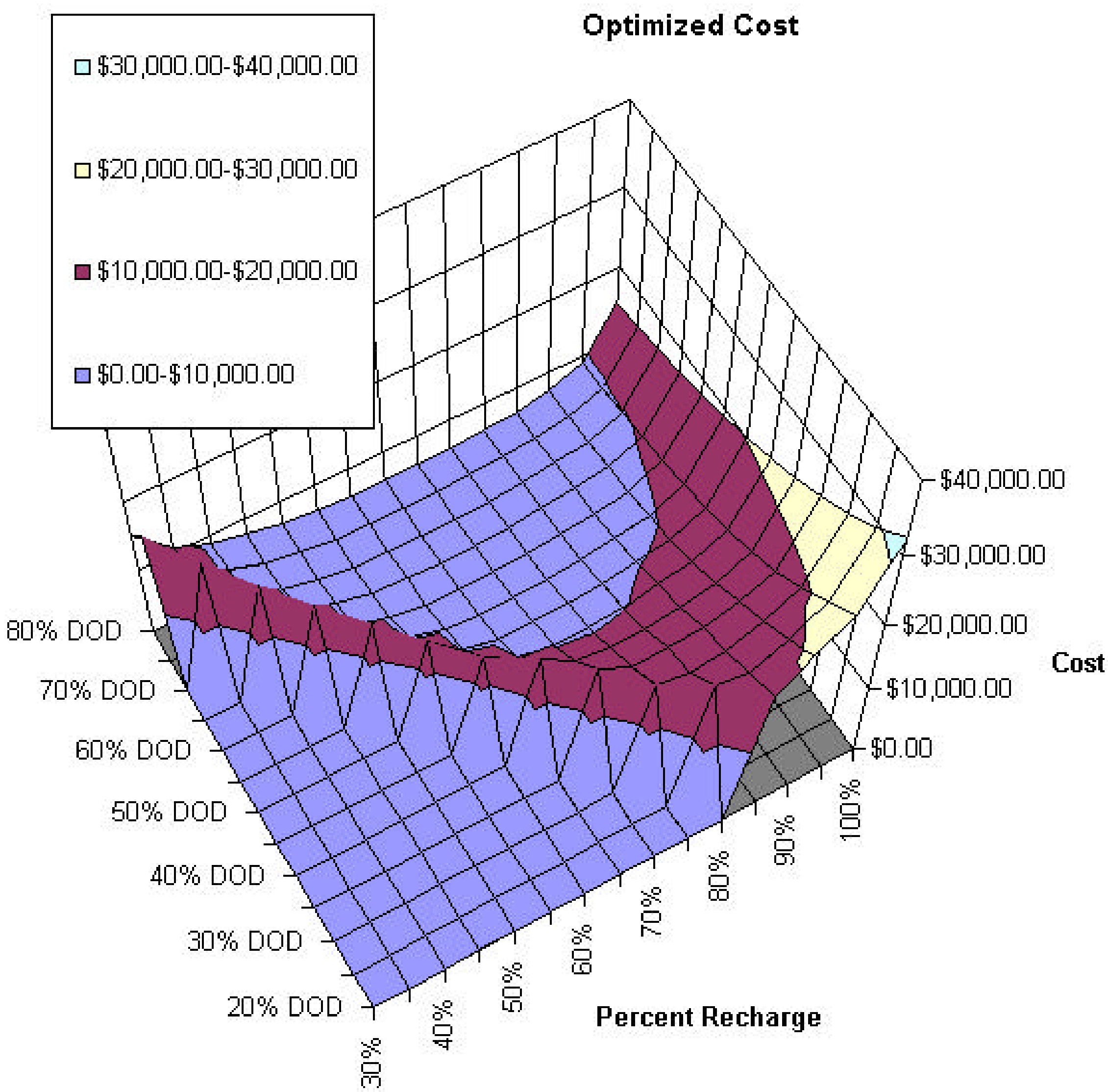

Figure 6-8. Cost Variation at Robert Barron without the Solar Contribution.

2. Predicted Output with the Solar Contribution

In this section, the optimal generator settings found in the previous sub-section, without the solar contribution, are hard-wired in the spreadsheet. Performance for each site is predicted based on these optimal generator settings calculated without the solar contribution for each site using the inputs shown in Figures (6-3) and (6-5) for Duke Island and Robert Barron, respectively.

a. Duke Island

Using the settings of 80% for Generator DOD and 70% for Generator %Recharge, the output shown in Figure (6-9) was produced. This output includes the solar contribution. The Battery DOD Prior to Generator Start (80%), Battery %Recharge Prior to Generator Stop (70%), Years Before Propane Tanks Refueled at Site (6.97), Years Until Batteries are Useless (11.75), and the Total Annual Cost ($4,814.62) provide a brief overview useful for comparison with the other simulations presented in this chapter.

Propane Generator Spreadsheet Calculated Outputs					
Generator Charging Cycles per Year (Battery Cycles Due to Generator)	Average Charging Generator Run-Time per Cycle (hrs.)	Charging Generator Run-Time per Year (hrs.)	Total Generator Run-Time per Year (hrs.)	Average Propane Fuel Consumed per Year (gal)	Propane Fuel Available for Generator at Site (gal)
64.10	3.9	250.01	250.81	250.81	2,000
Years Before Propane Tanks Refueled at Site	Total Generator Charging Cycles Prior to Refueling	Total Miscellaneous Generator Run-Time Prior to Refueling (hrs.)	Total Charging Generator Run-Time Prior to Refueling (hrs.)	Total Generator Run-Time Prior to Refueling (hrs.)	Total Amount of Propane Consumed Prior to Refueling (gal)
6.97	447.08	5.58	1,743.61	1,749.19	1,749.19

VRLA Battery Spreadsheet Calculated Outputs				
Battery DOD Prior to Generator Start	Battery %Recharge Prior to Generator Stop	Average Time Between Generator Starts (Discharge Time)	Number of Battery Cycles per Year Including Solar and Generator Processes	
80%	70%	132.85	326.10	
Percent Battery Cycles per Year Due to Generator Charging	Percent Battery Cycles per Year Due to Solar Charging	Discharge Rate (A/pos)	Battery Lifetime Available Cycles Including Solar and Generator Processes	Years Until Batteries are Useless
19.66%	80.34%	0.90	3,831.21	11.75

Spreadsheet Calculated Costs and Generator Settings					
Annual Cost of Propane	Annual Cost of Batteries	Total Annual Cost	Optimize Annual Cost (Click)	Generator Start Voltage Setting	Generator Finish Current Setting
$3,115.04	$1,699.58	$4,814.62	N/A		

Figure 6-9. Duke Island Results Using Generator Settings Found in Section C with the Solar Contribution.

b. Robert Barron

The same procedure used in this section for Duke Island is also used for Robert Barron. Using the optimal generator settings (80% DOD and 70% percent recharge) without the solar contribution produced the results in Figure (6-10). The Years Before Propane Tanks Refueled at Site (4.35), Years Until Batteries are Useless (12.30), and the Total Annual Cost ($4,546.18) provide a brief overview useful for comparison with the other simulations presented in this chapter.

Propane Generator Spreadsheet Calculated Outputs					
Generator Charging Cycles per Year (Battery Cycles Due to Generator)	Average Charging Generator Run-Time per Cycle (hrs.)	Charging Generator Run-Time per Year (hrs.)	Total Generator Run-Time per Year (hrs.)	Average Propane Fuel Consumed per Year (gal)	Propane Fuel Available for Generator at Site (gal)
133.29	3.9	519.84	523.31	523.31	2,800
Years Before Propane Tanks Refueled at Site	Total Generator Charging Cycles Prior to Refueling	Total Miscellaneous Generator Run-Time Prior to Refueling (hrs.)	Total Charging Generator Run-Time Prior to Refueling (hrs.)	Total Generator Run-Time Prior to Refueling (hrs.)	Total Amount of Propane Consumed Prior to Refueling (gal)
4.35	579.90	15.10	2,261.59	2,276.69	2,276.69

VRLA Battery Spreadsheet Calculated Outputs					
Battery DOD Prior to Generator Start	Battery %Recharge Prior to Generator Stop	Average Time Between Generator Starts (Discharge Time)		Number of Battery Cycles per Year Including Solar and Generator Processes	
80%	70%	61.87		214.29	
Percent Battery Cycles per Year Due to Generator Charging	Percent Battery Cycles per Year Due to Solar Charging	Discharge Rate (A/pos)	Battery Lifetime Available Cycles Including Solar and Generator Processes		Years Until Batteries are Useless
62.20%	37.80%	1.19	2,636.35		12.30

Spreadsheet Calculated Costs and Generator Settings					
Annual Cost of Propane	Annual Cost of Batteries	Total Annual Cost	Optimize Annual Cost (Click)	Generator Start Voltage Setting	Generator Finish Current Setting
$3,302.10	$1,244.08	$4,546.18	N/A		

Figure 6-10. Robert Barron Results Using Generator Settings Found in Section C with the Solar Contribution.

3. Optimization with the Solar Contribution

This section allows the spreadsheet to optimize the cost by changing generator settings with the solar contribution included.

a. Duke Island

The results illustrated in Figure (6-11) were simulated by the spreadsheet with the solar contribution. The Battery DOD Prior to Generator Start (70%), Battery %Recharge Prior to Generator Stop (35%), Years Before Propane Tanks Refueled at Site (39.45), Years Until Batteries are Useless (7.94), and the Total Annual Cost ($3,128.65) provide a brief overview useful for comparison with the other simulations presented in this chapter. The large number of Years Before Propane Tanks Refueled is a result of assuming a constant solar contribution per cycle. However, the actual length of the solar contribution per cycle decreases as the number of cycles per year increases. It is recommended that further testing be performed to determine the impact that a variable solar contribution has on the number of Years Before Propane Tanks Refueled.

The cost variation created during the simulation is pictured in the graph in Figure (6-12). The lowest costs calculated by the spreadsheet appear in the graph in the rectangular region delineated by 40% to 80% Generator DOD and 30% to 60% Generator %Recharge.

Propane Generator Spreadsheet Calculated Outputs

Generator Charging Cycles per Year (Battery Cycles Due to Generator)	Average Charging Generator Run-Time per Cycle (hrs.)	Charging Generator Run-Time per Year (hrs.)	Total Generator Run-Time per Year (hrs.)	Average Propane Fuel Consumed per Year (gal)	Propane Fuel Available for Generator at Site (gal)
162.16	0.3	48.65	49.45	49.45	2,000

Years Before Propane Tanks Refueled at Site	Total Generator Charging Cycles Prior to Refueling	Total Miscellaneous Generator Run-Time Prior to Refueling (hrs.)	Total Charging Generator Run-Time Prior to Refueling (hrs.)	Total Generator Run-Time Prior to Refueling (hrs.)	Total Amount of Propane Consumed Prior to Refueling (gal)
39.45	6,396.65	31.56	1,918.99	1,950.55	1,950.55

VRLA Battery Spreadsheet Calculated Outputs

Battery DOD Prior to Generator Start	Battery %Recharge Prior to Generator Stop	Average Time Between Generator Starts (Discharge Time)	Number of Battery Cycles per Year Including Solar and Generator Processes
70%	35%	53.76	424.16

Percent Battery Cycles per Year Due to Generator Charging	Percent Battery Cycles per Year Due to Solar Charging	Discharge Rate (A/pos)	Battery Lifetime Available Cycles Including Solar and Generator Processes	Years Until Batteries are Useless
38.23%	61.77%	0.90	3,368.21	7.94

Spreadsheet Calculated Costs and Generator Settings

Annual Cost of Propane	Annual Cost of Batteries	Total Annual Cost	Optimize Annual Cost (Click)	Generator Start Voltage Setting	Generator Finish Current Setting
$614.15	$2,514.50	$3,128.65	$3,128.65		

Figure 6-11. Duke Island Spreadsheet Optimized Generator Setting Results with the Solar Contribution.

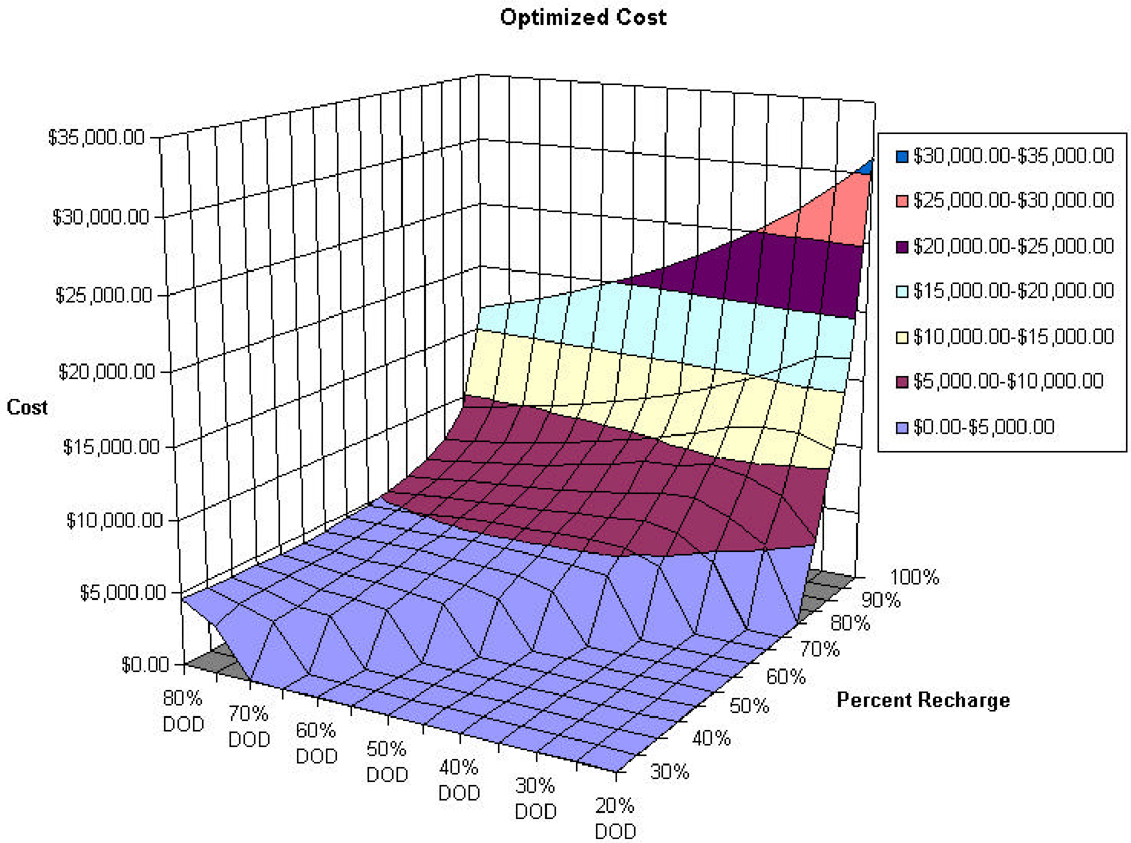

Figure 6-12. Duke Island Cost Variation with the Solar Contribution.

b. *Robert Barron*

The results illustrated in Figure (6-13) were simulated by the spreadsheet with the solar contribution for Robert Barron. The Battery DOD Prior to Generator Start (80%), Battery %Recharge Prior to Generator Stop (60%), Years Before Propane Tanks Refueled at Site (4.89), Years Until Batteries are Useless (10.10), and the Total Annual Cost ($4,516.71) provide a brief overview useful for comparison with the other simulations presented in this chapter.

The cost variation created during the simulation is pictured in the graph in Figure (6-14). The lowest costs calculated by the spreadsheet appear in the graph in the rectangular region delineated by 70% to 80% Generator DOD and 50% to 70% Generator %Recharge.

Propane Generator Spreadsheet Calculated Outputs					
Generator Charging Cycles per Year (Battery Cycles Due to Generator)	Average Charging Generator Run-Time per Cycle (hrs.)	Charging Generator Run-Time per Year (hrs.)	Total Generator Run-Time per Year (hrs.)	Average Propane Fuel Consumed per Year (gal)	Propane Fuel Available for Generator at Site (gal)
162.82	2.9	472.17	475.64	475.64	2,800
Years Before Propane Tanks Refueled at Site	Total Generator Charging Cycles Prior to Refueling	Total Miscellaneous Generator Run-Time Prior to Refueling (hrs.)	Total Charging Generator Run-Time Prior to Refueling (hrs.)	Total Generator Run-Time Prior to Refueling (hrs.)	Total Amount of Propane Consumed Prior to Refueling (gal)
4.89	795.66	16.96	2,307.41	2,324.36	2,324.36

VRLA Battery Spreadsheet Calculated Outputs					
Battery DOD Prior to Generator Start	Battery %Recharge Prior to Generator Stop	Average Time Between Generator Starts (Discharge Time)		Number of Battery Cycles per Year Including Solar and Generator Processes	
80%	60%	50.94		243.82	
Percent Battery Cycles per Year Due to Generator Charging	Percent Battery Cycles per Year Due to Solar Charging	Discharge Rate (A/pos)	Battery Lifetime Available Cycles Including Solar and Generator Processes		Years Until Batteries are Useless
66.78%	33.22%	1.19	2,462.43		10.10

Spreadsheet Calculated Costs and Generator Settings					
Annual Cost of Propane	Annual Cost of Batteries	Total Annual Cost	Optimize Annual Cost (Click)	Generator Start Voltage Setting	Generator Finish Current Setting
$3,001.26	$1,515.45	$4,516.71	$4,516.71		

Figure 6-13. Robert Barron Spreadsheet Optimized Generator Setting Results with the Solar Contribution.

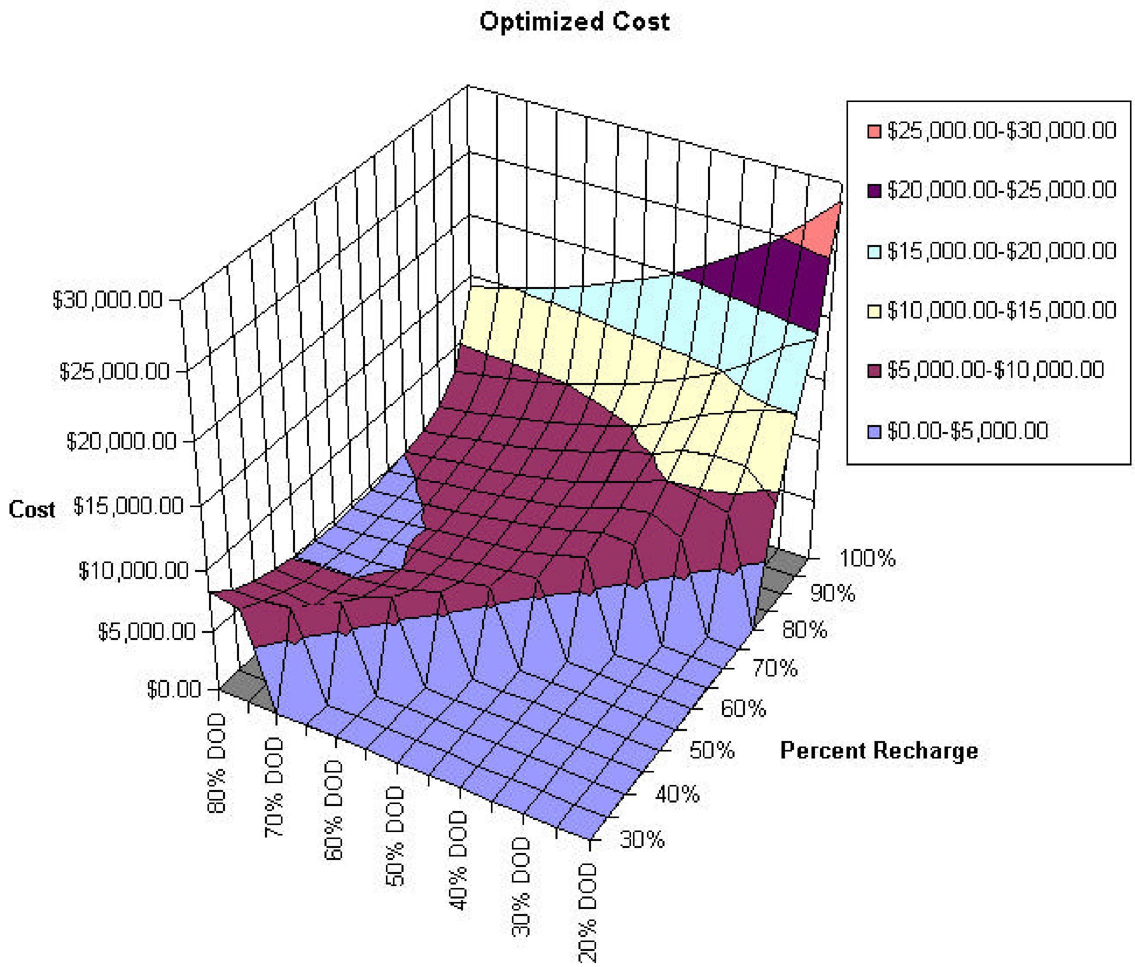

Figure 6-14. Robert Barron Cost Variation with the Solar Contribution.

E. ALTERNATIVE CONFIGURATION COST

The inputs remain the same to optimize for the alternative configuration. As mentioned previously, the duration of each charging process at a given Generator DOD and %Recharge relies on the same calculations used in the previous simulations. However, the added time between charging processes increases due to the increased capacity of the batteries from finish charging. The data shown in this section could only be achieved by adding additional battery strings and/or higher capacity batteries. Without additional battery capacity, the discharge rate would significantly increase during finish charging reducing the time in between charging processes. All results shown in this section include the solar contribution.

1. Duke Island

The results shown in Figure (6-15) simulate the increased performance of the alternative configuration at Duke Island. The Battery DOD Prior to Generator Start (75%), Battery %Recharge Prior to Generator Stop (30%), Years Before Propane Tanks Refueled at Site (83.91), Years Until Batteries are Useless (11.20), and the Total Annual Cost ($2,076.07) provide a brief overview useful for comparison with the other simulations presented in this chapter.

The graph in Figure (6-16) depicts the cost variation during the optimization process. The lowest costs calculated by the spreadsheet appear in the graph in the rectangular region delineated by 40% to 80% Generator DOD and 30% to 70% Generator %Recharge.

Propane Generator Spreadsheet Calculated Outputs

Generator Charging Cycles per Year (Battery Cycles Due to Generator)	Average Charging Generator Run-Time per Cycle (hrs.)	Charging Generator Run-Time per Year (hrs.)	Total Generator Run-Time per Year (hrs.)	Average Propane Fuel Consumed per Year (gal)	Propane Fuel Available for Generator at Site (gal)
75.85	0.3	22.76	23.56	23.56	2,000

Years Before Propane Tanks Refueled at Site	Total Generator Charging Cycles Prior to Refueling	Total Miscellaneous Generator Run-Time Prior to Refueling (hrs.)	Total Charging Generator Run-Time Prior to Refueling (hrs.)	Total Generator Run-Time Prior to Refueling (hrs.)	Total Amount of Propane Consumed Prior to Refueling (gal)
83.91	6,364.40	67.13	1,909.32	1,976.44	1,976.44

VRLA Battery Spreadsheet Calculated Outputs

Battery DOD Prior to Generator Start	Battery %Recharge Prior to Generator Stop	Average Time Between Generator Starts (Discharge Time)	Number of Battery Cycles per Year Including Solar and Generator Processes
75%	30%	115.27	337.85

Percent Battery Cycles per Year Due to Generator Charging	Percent Battery Cycles per Year Due to Solar Charging	Discharge Rate (A/pos)	Battery Lifetime Available Cycles Including Solar and Generator Processes	Years Until Batteries are Useless
22.45%	77.55%	0.90	3,782.39	11.20

Spreadsheet Calculated Costs and Generator Settings

Annual Cost of Propane	Annual Cost of Batteries	Total Annual Cost	Optimize Annual Cost (Click)	Generator Start Voltage Setting	Generator Finish Current Setting
$292.55	$1,783.52	$2,076.07	$2,076.07		

Figure 6-15. Duke Island Alternative Configuration Optimization with the Solar Contribution.

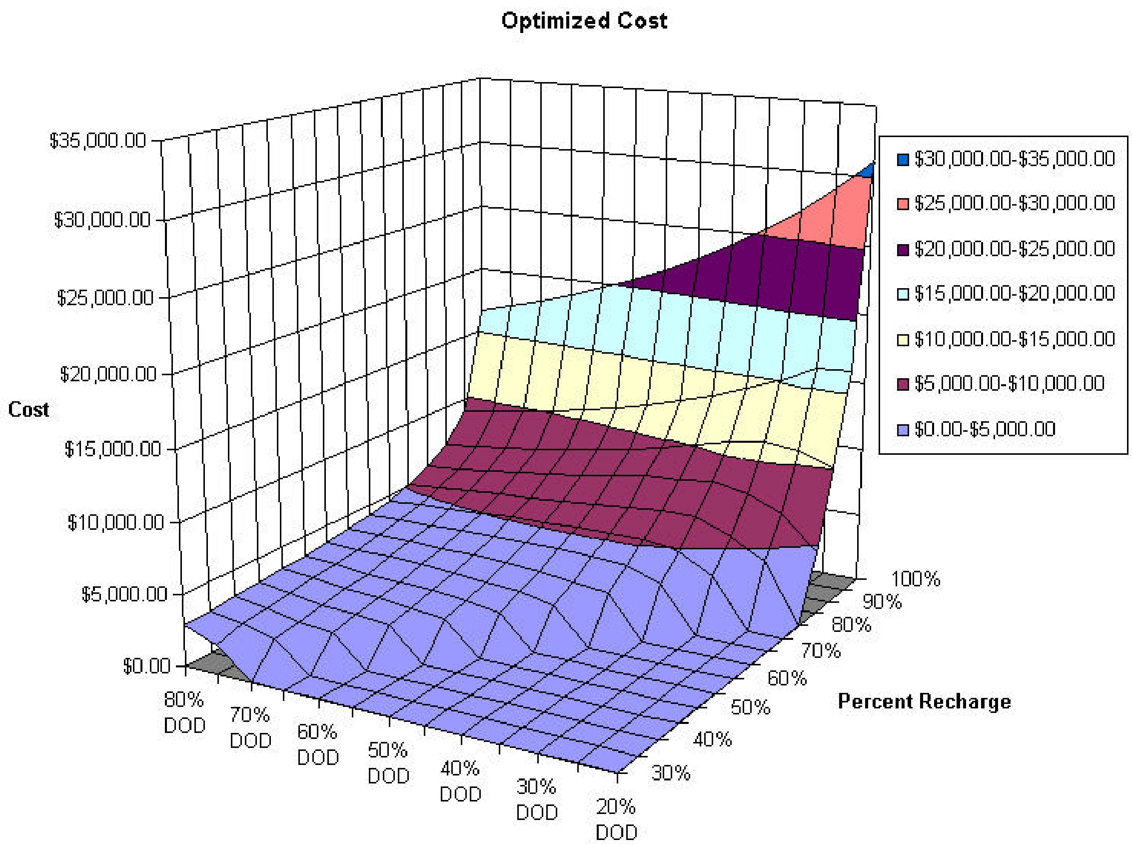

Figure 6-16. Duke Island Cost Variation for Alternative Configuration with the Solar Contribution.

2. Robert Barron

The results shown in Figure (6-17) indicate an increase in performance at Robert Barron through the use of the alternative configuration. The Battery DOD Prior to Generator Start (75%), Battery %Recharge Prior to Generator Stop (30%), Years Before Propane Tanks Refueled at Site (50.10), Years Until Batteries are Useless (10.12), and the Total Annual Cost ($1,858.74) provide a brief overview useful for comparison with the other simulations presented in this chapter.

Figure (6-18) depicts the cost variation during the optimization process. The lowest costs occur when the Generator DOD ranges roughly between 35% and 80% while the Generator %Recharge varies between 30% and 65%.

Propane Generator Spreadsheet Calculated Outputs					
Generator Charging Cycles per Year (Battery Cycles Due to Generator)	Average Charging Generator Run-Time per Cycle (hrs.)	Charging Generator Run-Time per Year (hrs.)	Total Generator Run-Time per Year (hrs.)	Average Propane Fuel Consumed per Year (gal)	Propane Fuel Available for Generator at Site (gal)
171.08	0.3	51.32	54.79	54.79	2,800
Years Before Propane Tanks Refueled at Site	Total Generator Charging Cycles Prior to Refueling	Total Miscellaneous Generator Run-Time Prior to Refueling (hrs.)	Total Charging Generator Run-Time Prior to Refueling (hrs.)	Total Generator Run-Time Prior to Refueling (hrs.)	Total Amount of Propane Consumed Prior to Refueling (gal)
50.10	8,571.18	173.85	2,571.36	2,745.21	2,745.21

VRLA Battery Spreadsheet Calculated Outputs				
Battery DOD Prior to Generator Start	Battery %Recharge Prior to Generator Stop	Average Time Between Generator Starts (Discharge Time)	Number of Battery Cycles per Year Including Solar and Generator Processes	
75%	30%	50.94	252.08	
Percent Battery Cycles per Year Due to Generator Charging	Percent Battery Cycles per Year Due to Solar Charging	Discharge Rate (A/pos)	Battery Lifetime Available Cycles Including Solar and Generator Processes	Years Until Batteries are Useless
67.87%	32.13%	1.19	2,550.00	10.12

Spreadsheet Calculated Costs and Generator Settings					
Annual Cost of Propane	Annual Cost of Batteries	Total Annual Cost	Optimize Annual Cost (Click)	Generator Start Voltage Setting	Generator Finish Current Setting
$345.74	$1,512.99	$1,858.74	$1,858.74		

Figure 6-17. Robert Barron Alternative Configuration Optimization with the Solar Contribution.

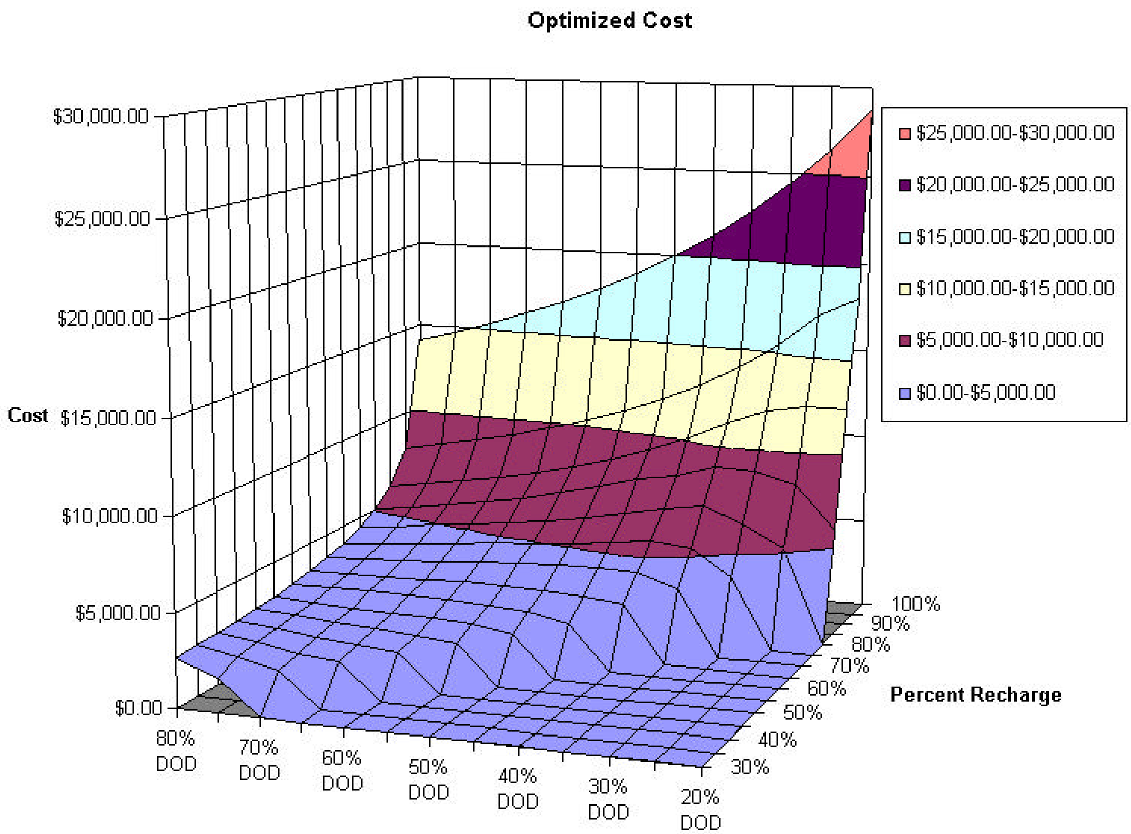

Figure 6-18. Robert Barron Cost Variation for Alternative Configuration with the Solar Contribution.

F. SUMMARY

The results of the simulations performed in this chapter are summarized in this section.

Table (6-1) illustrates the costs associated with the DOD and percent recharge values calculated at Duke Island and Robert Barron for the current settings.

	Duke Island	**Robert Barron**
Generator DOD	60%	60%
Generator %Recharge	85%	85%
Cost	$8616.92	$7208.47

Table 6-1. Current Settings Cost.

Table (6-2) summarizes the costs associated with the optimized generator settings found without the solar contribution when plugged into the spreadsheet with the solar contribution.

	Duke Island	Robert Barron
Generator DOD	80%	80%
Generator %Recharge	70%	70%
Cost	$4814.62	$4546.18

Table 6-2. Cost Associated with Settings Determined without the Solar Contribution Inputted into Spreadsheet with the Solar Contribution.

Table (6-3) displays the costs associated with the optimized generator settings found with the solar contribution.

	Duke Island	Robert Barron
Generator DOD	70%	80%
Generator %Recharge	35%	60%
Cost	$3128.65	$4516.71

Table 6-3. Cost Associated with Settings Determined with the Solar Contribution.

Table (6-4) shows the costs associated with the alternative configuration optimized with the solar contribution.

	Duke Island	Robert Barron
Generator DOD	75%	75%
Generator %Recharge	30%	30%
Cost	$2076.07	$1858.74

Table 6-4. Cost Associated with Alternative Configuration Settings Determined with the Solar Contribution.

The preliminary simulation results indicate that a cost savings is realizable through improved generator settings. Further investigation should occur prior to implementing any of the settings tested to verify their reliability.

The accuracy of the results obtained during these simulations could be improved if battery performance plots were generated at each Generator DOD and %Recharge combination simulated in the spreadsheet. Additionally, the fuel consumption rate slightly varies with the output current of the Mechron RBS system. It is recommended that further research be performed to use more accurate values for discharging and charging durations based on battery performance plots generated at all applicable DOD and percent recharge combinations. Also, the fuel consumption rate used in the simulations should be verified and if needed, corrected to improve the accuracy of the spreadsheet calculated results.

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VII. CONCLUSION

A. FOREWORD

This chapter highlights accomplishments made in this thesis effort and offers recommendations. Hybrid power system redesign issues including wind turbine power, various battery technologies, and Amp-Hour counting are identified in Section B. Section C summarizes the optimal results calculated by the spreadsheet. Section D lists the accomplishments of this research. Section E concludes this chapter providing recommendations for future work.

B. REDESIGN ISSUES

1. Wind Turbine

The need for a renewable energy source during the winter months such as wind turbine power has not diminished since the inception of the NDS sites of Robert Barron and Duke Island. Currently, the probability of finding a system that can withstand the extreme weather conditions at these two sites is limited. It is recommended that as technology advances the reliability and durability of wind turbine power, further investigation into the potential of installing wind turbine power systems at specific NDS sites be conducted.

2. Battery Technology

There have been significant advances in battery technology during the recent past. As these advancements continue, the ability to provide large amounts of energy storage in a small area will continue to expand. Since one of the major expenses of operating the NDS sites is transportation of lead-acid batteries (primarily due to their heavy weight), further consideration should be given to more advanced batteries that have higher energy densities and consequently take up less space and weigh less than traditional lead-acid batteries. As the cost of these more advanced batteries decreases, the feasibility of using them for energy storage at NDS sites will improve.

3. Amp-Hour Counting

To ensure proper execution of the desired charging process, more precise measures should be implemented to determine battery SOC. Amp-Hour counting is one such method. As a result, the exact discharge rate of the batteries as well as the number of Amp-Hours discharged at any point can be calculated. By knowing the discharge rate, experimental measurements can be performed to determine the capacity under specified environmental conditions. The theoretical capacity can then be modified for the effects of temperature. Finally, the resulting capacity is multiplied by the percentage obtained when the SOC at the desired DOD is subtracted from the desired percent recharge. This overall quantity in Amp-Hours is the capacity used each cycle. Once the Amp-Hour counting system reaches the number of Amp-Hours specified by this capacity, the generator starts. The generator runs until a specified number of Amp-Hours is replaced as determined by the predetermined percent recharge. This method allows precise instruments to make incremental adjustments to the capacity available for each cycle. The method currently used at Robert Barron and Duke Island relies on the user to make the incremental changes. Since, settings are changed very rarely at these two sites, the possibility that the current settings do not reflect the desired DOD and percent recharge is real. It is recommended that efforts be made to assess the potential factors surrounding the installation of an Amp-Hour counting system.

C. ANALYSIS SUMMARY

The results from Chapter VI indicate that the most cost efficient manner of operating the generators at Robert Barron and Duke Island is not currently taking place. With current generator settings (60% DOD and 85% Recharge, at each site), the annual cost to operate Duke Island is projected to be $8,616.92 while the projected cost at Robert Barron is expected to be $7,208.47. According to the least optimistic results found using the generator settings determined without the solar contribution (80% DOD and 70% Recharge), the annual cost at Duke Island could be reduced to $4,814.62. At Robert Barron using the same generator settings as Duke Island, the annual cost could be reduced to $4,546.18. The numbers for the alternative configuration show that after new equipment and battery capacity are installed, it could provide a substantial savings over the currently projected costs resulting in annual costs estimated to be $2,076.07 and $1,858.74 for Duke Island and Robert Barron, respectively.

D. RESEARCH SUMMARY

The following was accomplished in this thesis effort:

- Thorough estimation of the loads and characterization of the equipment at Robert Barron and Duke Island,

- Succinct overview of lead-acid battery theory,
- Identification of various battery technologies available today,
- Brief description of how the fuzzy logic controller operates,
- Mathematical model (spreadsheet) to predict the performance of the generators and batteries at each site,
- Preliminary recommendations surrounding optimal generator settings,
- Future cost predictions at each site,
- Description of the alternative configuration that could prove to be a beneficial addition to each site,
- Suggestions to improve the accuracy of the results obtained during simulations.

E. FUTURE WORK

A major cause for a lack of confidence in the spreadsheet results stems from the difficulty encountered during the mathematical modeling process applied in the spreadsheet. This lack of confidence is almost entirely created by the pseudo-random variation in the power provided by the solar arrays. Serious consideration regarding further experimentation to ascertain the validity of averaging the contribution from solar over each cycle is recommended.

There are also potential inaccuracies in the spreadsheet from a lack of data provided by the battery manufacturer. It is recommended that actual laboratory experimentation be done to determine various charging and discharging durations associated with different DODs, percent recharges, and discharge rates. To ensure the accuracy of the spreadsheet, Figure (2-3) or an equivalent representation should be generated for each DOD and percent recharge tested in the spreadsheet. Figure (2-2) or an equivalent representation should also be generated at several more discharge rates. From these experiments, more accurate discharging and charging durations could be implemented in the spreadsheet.

After experimentation is completed and assuming the spreadsheet is an accurate predictor of performance at the NDS sites, it may be possible to perform a cost analysis with various battery technologies. This could prove useful in the future when the battery costs associated with advanced technology decrease to more affordable levels to help identify replacement batteries for the VRLA batteries when they are no longer able to support their respective load at each site.

APPENDIX A. MICROSOFT VISUAL BASIC CODE

The following code was used to find the lowest cost during spreadsheet simulations:

```
Sub MinimizeCost()
'
' MinimizeCost Macro
' Macro recorded 4/4/2002 by zaweiss
'
Range("A25").Select
ActiveCell.Value = 0.2
Range("B25").Select
ActiveCell.Value = 1
'
Range("C32").Select
cost = ActiveCell.Value
'
r = 13
x = 0
c = 1
lowcost = cost
For i = 0.2 To 0.75 Step 0.05
c = c + 1
r = r - x - 1
x = 0
For j = (1.05 - i) To 1.05 Step 0.05
Range("A25").Select
ActiveCell.Value = i
Range("B25").Select
ActiveCell.Value = j
Range("C32").Select
cost = ActiveCell.Value

r = r + 1
x = x + 1
Worksheets("Output").Activate

Cells(r, c).Value = cost

Worksheets("Inputs and Outputs").Activate

If lowcost >= cost Then
lowcost = cost
ilow = i
```

```
jlow = j

Range("d32").Select
ActiveCell.Value = lowcost
End If

Next j
Next i

For i = 0.75 To 0.85 Step 0.05
c = c + 1
r = 1
For j = 0.3 To 1.05 Step 0.05
Range("A25").Select
ActiveCell.Value = i
Range("B25").Select
ActiveCell.Value = j
Range("C32").Select
cost = ActiveCell.Value

r = r + 1
Worksheets("Output").Activate

Cells(r, c).Value = cost

Worksheets("Inputs and Outputs").Activate

If lowcost >= cost Then
lowcost = cost
ilow = i
jlow = j

Range("d32").Select
ActiveCell.Value = lowcost
End If
Next j
Next i
Range("a25").Select
ActiveCell.Value = ilow
Range("b25").Select
ActiveCell.Value = jlow

End Sub
```

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   USCG MLCPAC TE-3
   Alameda, California

7. Dan Slagle
   USCG MLCPAC TE-3
   Alameda, California

8. Garth Corey
   Sandia National Laboratories
   Albuquerque, New Mexico

9. Chris Doreleyers
   Mechron Power Systems
   Ottawa, Ontario, Canada

10. Zachary Weiss
    USCG MLCPAC TE-3
    Alameda, California